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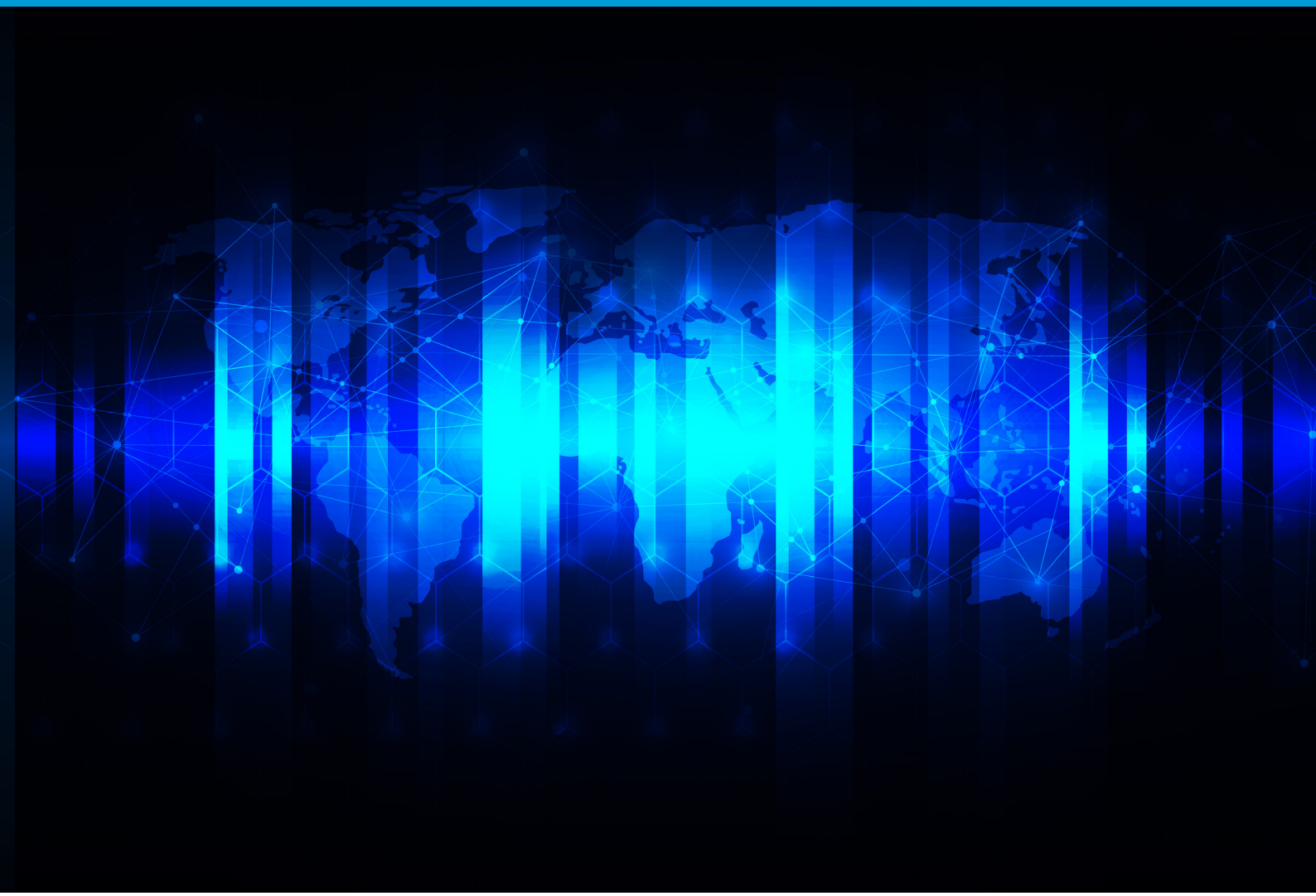
Radiocommunication Sector

Handbook on Spectrum monitoring

Edition of 2026



Handbook on Spectrum Monitoring

Edition of 2026

Radiocommunication Bureau

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PREFACE

In the year 2023, Radiocommunication Study Group 1 agreed with Working Party 1C decision to initiate the revision of the ITU Spectrum Monitoring Handbook (edition 2011), taking into account the latest developments in digital radio systems and the needs of spectrum management regulatory authorities, in particular, those of developing countries.

After initial preparatory work carried out in a Correspondence Group, Working Party 1C established a Rapporteur Group, involving worldwide Experts from many administrations, operators and manufacturers, to prepare this sixth edition of the Handbook. Working Party 1C and its Rapporteur Group successfully completed their work as planned, and this new edition of the Handbook was approved by Study Group 1 in June 2026. Containing the latest information on all aspects of monitoring (including equipment, procedures and applications of artificial intelligence), the Handbook represents a valuable reference manual for the spectrum management community.

The eight Chapters describe in detail the key elements of spectrum monitoring and its relationship to spectrum management. In addition, the Handbook contains many references that can be consulted for additional details.

The Handbook on Spectrum Monitoring is intended for the use by administrations of both developing and developed countries and by the Radiocommunication Bureau. The Handbook will also be useful to radiocommunication engineers everywhere.

Mario Maniewicz

Director, Radiocommunication Bureau

TABLE OF CONTENTS

Page

PREFACE iii

TABLE OF CONTENTS v

FOREWORD vii

Acknowledgements viii

INTRODUCTION ix

CHAPTER 1 – Spectrum monitoring as a key function of a spectrum management system 1

CHAPTER 2 – Organization, Physical Structures and Personnel 33

CHAPTER 3 – Monitoring stations and equipment 79

CHAPTER 4 – Data management, automation and networking 175

CHAPTER 5 – Measurements 231

CHAPTER 6 – Specific monitoring systems and procedures 429

CHAPTER 7 – Fundamentals and supporting tools 625

CHAPTER 8 – Monitoring system planning and tenders 705

List of the abbreviations used in the Handbook 745

FOREWORD

In view of the continuously increasing demand for the radio-frequency spectrum, it is essential that spectrum monitoring techniques evolve in step with advances in radiocommunication technologies and that such knowledge is effectively shared worldwide. Since the publication of 2011 edition of this Handbook, notable progress has been achieved in monitoring methodologies and technologies. In response to these developments, Study Group 1 of the ITU Radiocommunication Sector (ITU-R) entrusted its Working Party 1C (WP 1C) with the task of revising the Handbook on Spectrum Monitoring for the benefit of developing and developed countries.

The radio frequency spectrum is a limited natural resource, and it is essential that it is used in the most effective and efficient manner by all radiocommunication users around the world. This ensures that various radiocommunication networks can function in an interference-free radio environment. With the rapid evolution of radiocommunication technologies, including the expansion of broadband systems, advanced wireless applications, and satellite services, the demand for spectrum and orbital resources continues to grow significantly. Consequently, effective and efficient spectrum management is the key element for ensuring the co-existence of various radiocommunication networks, without causing interference to each other.

Spectrum monitoring is one of the essential tools of spectrum management and its techniques are developed to ensure that technical parameters and standards for radiocommunication systems are adhered to. In addition, spectrum monitoring assists in promoting the efficient utilisation of the radio frequency spectrum and the satellite orbit. Spectrum monitoring techniques are different from those of a radiocommunication network in that they are carried out in non-optimal situations and in an unknown environment.

This Handbook has been developed covering all essential features of spectrum monitoring techniques and activities including the establishment of monitoring facilities. The Handbook is expected to be of great value to administrations and spectrum monitoring agencies. It is considered to be equally valuable to the developing as well as to developed countries. Compared to the previous edition and to be in line with new development in the field of spectrum monitoring, this edition includes restructuring some of the previous texts and the development of new chapters.

We convey our great appreciation to Mr Thomas Hasenpusch (Germany), Rapporteur chairing the WP 1C Rapporteur Group (2024-2026) on the complete revision of the Handbook, Mr Mubarak Al-Sawafi (Oman), acting Rapporteur chairing previously this group (2023-2024) and Mr Ralf Trautmann (Germany), former WP 1C Chair, who chaired the WP 1C Correspondence Group on the preparation of this revision of the Handbook (2019-2023). Our appreciations go also to the Rapporteurs of the various chapters of the Handbook, to the contributors, participants and all those who have been instrumental in the development of this new edition of the Handbook, without whose efforts this excellent publication would not have been a reality. Our special gratitude is also due to Mr Philippe Aubineau, Counsellor of the Radiocommunication Bureau who has played a key role in the development of the Handbook.

It is hoped that this new edition of the Handbook will continue to prove being a great asset in the field of spectrum management and spectrum monitoring for establishment and operation of monitoring facilities. It should continue to provide essential tools for spectrum management and for the performance of radiocommunication networks in an interference-free environment.

Wael Sayed

Chair, ITU-R Study Group 1
on Spectrum Management

Mubarak Al-Sawafi

Vice-Chair, ITU-R Study Group 1
Chair, ITU-R Working Party 1C
on Spectrum Monitoring

Acknowledgements

The rapporteur group express its appreciation to all ITU membership who supported the development of this Handbook for their contributions, participation and hosting of meetings.

The following individuals, listed in alphabetical order, provided substantive contributions to this new edition of the Handbook on Spectrum Monitoring. The relevant Chapter and Section numbers are given in parentheses.

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We would also like to thank the many others who have contributed to the Handbook by participating in meetings and providing fruitful advice and comments.

INTRODUCTION

The purpose of this Handbook

The purpose of spectrum monitoring is to support the spectrum management process in general and, in particular, to detect, identify and resolve radio interference. However, spectrum monitoring must not be misunderstood as radio surveillance. In spectrum monitoring the content of an emission may be used to identify a radio station or to determine the service quality. However, the message as such is of no interest.

The purpose of this Handbook, developed in accordance with Resolution ITU-R 1, is to provide key reference information to all those who are involved in the process of spectrum monitoring: managers, operators, maintenance staff, instructors and procurement managers.

A short historical retrospect

The CCIR published the first edition of the Handbook for Monitoring Stations in 1968 (supplemented in 1971). The next edition was published 20 years later in 1988. Just a few years later in 1995 there was a need for the publication of a further edition with a major revision of the handbook structure.

The 2002 edition solved the issue of a clear separation between sections related to equipment and measurement procedures. The structure of that edition still formed the basis for the following new editions. This edition was partially updated in 2008 by the Supplement to the Handbook on Spectrum Monitoring, including new material for Chapter 3 on monitoring equipment and automation of monitoring operations, Section 5.1 on spacecraft emission monitoring and Annex 1 on monitoring system planning and tenders. Finally, a complete revision of the Handbook was published in 2011 where the separation between the various chapters was further improved, old material was updated and a lot of new material was incorporated, e.g. the introduction of radar measurement techniques and measurements on time difference of arrival.

The development of this edition

In response to developments in telecommunication and monitoring technology and the proposals received from membership, ITU-R Working Parity 1C (WP 1C) decided at its meeting in May/June 2019 to establish a Correspondence Group (CG) chaired by Mr Ralf Trautmann (Germany) to consolidate contributions and proposals on sections of the Handbook to be revised, for the insertion of new sections, for the structure of the new Handbook and for a possible Rapporteur to chair a Rapporteur Group (RG) and possible Chapter Rapporteurs. The CG was also tasked to develop draft Terms of Reference for the RG on developing a new edition of the ITU Handbook on Spectrum Monitoring.

To progress the work, WP 1C decided at its meeting in May/June 2023 to disband the previous CG and install an RG for this activity and develop the Terms of Reference (ToR) for this RG (the 1C-RG-SMH). It was also agreed to identify the management team i.e. Rapporteur and chapter Rapporteurs for the development of a new edition of the Handbook. The Vice-Chair of WP 1C, Mr Mubarak Al-Sawafi (Oman (Sultanate of)) was agreed to be the acting Rapporteur for the 1C-RG-SMH till the appointment of new Rapporteur.

Subsequently, WP 1C decided at its meeting in May/June 2024 to appoint Mr Thomas Hasenpusch (Germany) as the Rapporteur of the 1C-RG-SMH. In addition to work in a Working Group during annual meetings of WP 1C, the RG held three separate meetings solely dedicated to the Handbook: 5-12 November 2024 in Geneva, 10-14 November 2025 in Geneva and 23-27 March 2026 in Munich.

More than 100 input documents submitted by ITU Member States, ITU-R Sector Members and ITU-R SG 1 Associates (e.g. equipment manufacturers) and Liaison Statements from other ITU Groups resulted in amendments to and revisions of existing sections as well as completely new Chapters and sections. These contributions in turn resulted in proposals for the modification and improvement of the handbook structure. which was continuously refined throughout the revision process which resulted in a substantially text with improved logical delimitation between the various Chapters.

The text of this Handbook was approved by SG 1 during its meeting in June 2026 in Geneva.

The Handbook consists of the following parts, with the responsible Chapter Rapporteurs indicated on the right:

Chapter 1	Spectrum monitoring as a key function of spectrum management system	Mr Titus Cheptoo (Kenya)
Chapter 2	Organization, Physical Structures and Personnel	Mr Salvatore Lamparella (Telespazio, Italy)
Chapter 3	Monitoring Stations and Equipment	Dr Roy B. Woolsey (TCI International, Inc)
Chapter 4	Data management, Automation and Networking	Mr Fábio Lobão (Brazil)
Chapter 5	Measurements	Mr Felix Schad (Germany)
Chapter 6	Specific monitoring systems and procedures	Dr Haim Mazar (ATDI, France)
Chapter 7	Fundamentals and supporting tools	Mr Thomas Hasenpusch (Germany)
Chapter 8	Monitoring system planning and tenders	Mr Arseny Plossky (Russian Federation)

In addition, the following Rapporteurs were responsible for some sub-chapters or sections:

Sub-Chapter 4.5	Process and analysis	Mr Kanghee Kim and Mr Byung Chan Kim (Korea (Rep. of))
Sub-Chapter 6.1	Monitoring of spacecraft emissions	Mrs Luo Chao (China)
Sub-Chapter 6.3 Sub-Chapter 6.7	Monitoring of cellular systems Radio noise measurements	Mr Thomas Hasenpusch (Germany)
Sub-section 7.1	Radio Navigation Satellite Service (RNSS)	Dr Haim Mazar (ATDI, France)
Sub-section 8.2 Sub-section 8.3	General overview of a tender process Preparation stage: planning	Dr Alexander Pavlyuk (Russian Federation)

NOTE – While care is taken to refer to the official definition of IMT-generations as defined in Resolution ITU-R 56 'Naming for International Mobile Telecommunications', parts of this handbook contain material, which refers to the frequently used market names “xG”. In general, IMT-2000, IMT-Advanced, IMT-2020 and IMT-2030 are known as 3G/4G/5G/6G, respectively.

What the Chapters contain

Chapter 1 describes the tasks of the spectrum monitoring service, the relationship between spectrum monitoring and spectrum management and the international monitoring system.

Chapter 2 describes the structure and organisation of a spectrum monitoring service including siting of monitoring stations, personnel for operation and maintenance.

Chapter 3 describes the different types of monitoring stations and equipment which are used to perform the measurements. This Chapter is mainly of interest for staff involved in the planning and procurement of monitoring equipment.

Chapter 4 is a new chapter that was created due to the increasing importance and complexity of monitoring data acquisition and evaluation. The Chapter elaborates hardware, software and design of monitoring networks, their management, processing and storage of monitoring data, including the upcoming usage of Artificial Intelligence (AI).

Chapter 5 describes measurements of basic RF parameters such as level, frequency, bandwidth and modulation. In addition, it describes combined measurement procedures such as direction-finding, localisation and coverage.

Chapter 6 describes specific monitoring systems and procedures that are either not carried out by all spectrum monitoring services, apply service- or technology-dependent methods, or require specific equipment. Examples are monitoring of spacecraft emissions, monitoring of cellular systems and EMF measurements.

Chapter 7 discusses relevant physical basics such as Fast Fourier Transform, modulation and spectrum access methods. It also contains information on supplementary tools such as maps, and the required documentation.

Chapter 8 on monitoring system planning and tenders provides also necessary information on economic aspects on spectrum monitoring, which is essential for those who are involved in the process of equipment procurement. It used to be referred to as Annex 1 in the former edition of the Handbook.

Conclusion

The new Handbook text is suitable to serve for the coming years the demands of readers from both developing and developed countries, who want to gather up-to-date information about a radio monitoring service's organisation, equipment and measurement techniques.

I would like to thank all Chapter and Section Rapporteurs, all contributors and participants of the various meetings and the WP 1C Chair for their valuable contributions, comments and advice. Last but not least, I would like to thank Mr Philippe Aubineau, the Counsellor for ITU-R SG 1, for his support. Without his incredible precision and speed in identifying any inconsistencies, the Handbook would have not been available in this quality.

Thomas HASENPUSCH
Rapporteur of the RG
on the Spectrum Monitoring Handbook

CHAPTER 1

Spectrum monitoring as a key function of a spectrum management system

TABLE OF CONTENTS

Page

1.1 Overview of spectrum management 3

1.1.1 Legal and regulatory framework for national spectrum management 4

1.1.2 ITU rules, regulations and associated standards 5

1.1.3 Spectrum planning and allocation 5

1.1.4 Spectrum engineering 6

1.1.5 Frequency coordination and notification 6

1.1.6 Licensing, assignment and billing 7

1.1.7 Spectrum monitoring 7

1.1.8 Inspection of radio installations 8

1.1.9 Law enforcement 9

1.2 Spectrum management considerations 9

1.2.1 Efficient use of spectrum 9

1.2.2 Spectrum sharing 9

1.2.3 Economic aspects 11

1.3 Spectrum monitoring goals 12

1.3.1 Monitoring for compliance with national rules 12

1.3.2 Monitoring to aid spectrum management policy 14

1.4 Spectrum monitoring tasks 15

1.4.1 Tasks derived from the Radio Regulations 15

1.4.2 Tasks on a national basis 16

1.4.3 Co-operation of radio monitoring and inspection services 16

1.4.4 Co-operation of radio monitoring with other bodies 17

1.4.5 Measurement tasks and essential equipment 17

1.5 Relationship between spectrum monitoring and spectrum management 18

1.6 International monitoring 19

1.6.1 Centralising office and international cooperation 19

1.6.2 The international monitoring system 20

Page

1.6.3 Coordination role of the Bureau 20

1.6.4 Use of international monitoring data by the Bureau 21

1.6.5 International monitoring programmes 22

1.6.6 Global monitoring coverage 23

1.7 Collaboration among monitoring stations of different countries 23

1.7.1 Collaboration below 30 MHz 24

1.7.2 Collaboration above 30 MHz 24

1.7.3 Collaboration on the monitoring of space emissions 25

Annex 1 to Chapter 1 – Agreement, protocol and model cross border agreement for direct co-operation among radio monitoring stations 26

PROTOCOL Regarding the Agreement of 1993 among the Administrations of Germany, Switzerland and France on the direct co-operation between radio monitoring stations 27

MODEL CROSS BORDER AGREEMENT 28

References 30

1.1 Overview of spectrum management

Spectrum management is the overall process of regulating and coordinating the utilization of the radio frequency spectrum involving the application of administrative, scientific and technical procedures necessary to ensure the orderly development and deployment of radio equipment and services without causing interference. Spectrum management also deals with the resolution of interference to radio communication services that may be caused by any transmitting radio equipment and/or Industrial Scientific and Medical (ISM) devices. Rules and regulations, based on relevant legislation, form the regulatory and legal basis for the spectrum management process. Databases containing information on all the authorized users and technical information of the radiocommunication stations and networks provide the administrative and technical basis for the process.

The key objectives of spectrum management are to:

– maximize spectrum efficiency;

– minimize interference;

– eliminate unauthorized and improper use of the spectrum;

– allocate radio spectrum to stakeholders for the development of new wireless technologies and services.

The components of spectrum management process can broadly be summarized as:

– spectrum planning and allocation;

– spectrum engineering:

– coordination and notification;

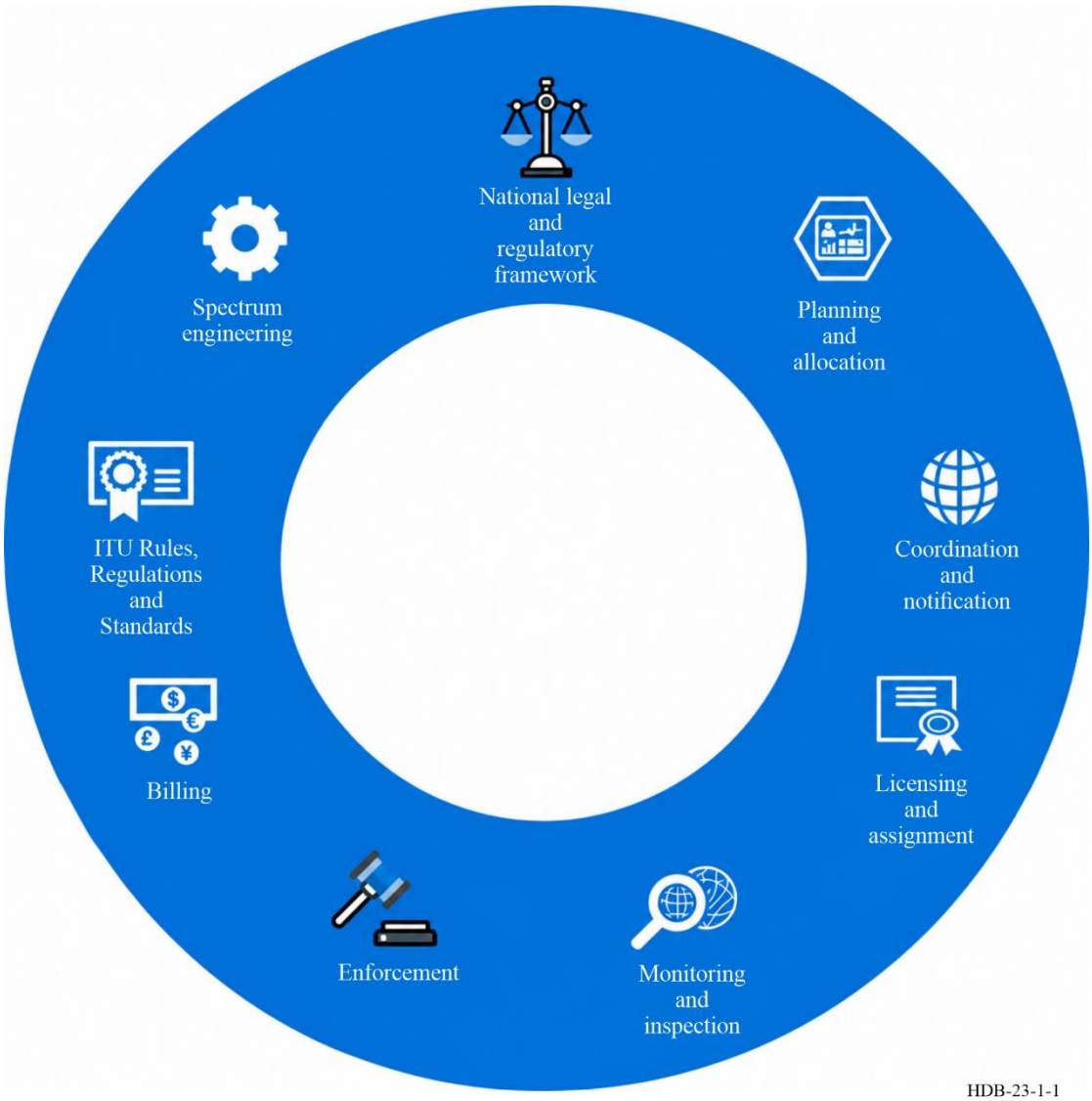
– frequency licensing and assignment;

– billing (valuation, auctioning and pricing);

– monitoring and inspection.

These components are supported by the national legal and regulatory framework, ITU rules, regulations and standards, as well as spectrum databases and spectrum enforcement as illustrated in Fig. 1-1.

FIGURE 1-1



For more information on these related spectrum management issues, refer to the latest edition of the publications: ITU Handbook on National Spectrum Management, ITU Handbook on Computer-Aided Techniques for Spectrum Management (CAT), Reports ITU-R SM.2012, ITU-R SM.2015, ITU-R SM.2093, ITU-R SM.2130 and WTDC Resolution 9.

1.1.1 Legal and regulatory framework for national spectrum management

Because of the rapid advance of radio technology and the central role that technology plays in the life of each nation, laws covering the spectrum resources are becoming as important as those that govern land and water use. Therefore, the use and regulation of radiocommunications have to be covered within each nation's body of law. The radiocommunications law is a basic document establishing concepts, authorities, broad goals and objectives, and responsibilities, but should not stray into detailed delineation of regulations and procedures. This law should give recognition to the radio spectrum as a national resource and the need to govern it in the interest of all citizens. It should establish the right of the national government to regulate radio communications use, including authorization for use and enforcement of spectrum management rules, primarily controlled through monitoring and inspection. To carry out these functions, spectrum managers should be granted the authority to identify sources of interference and to require that they be turned off or confiscated under an appropriate legal mechanism. The limits of the authority should also be specified.

The radiocommunications law should establish the right of both citizens and government to own and operate radio equipment. National, regional or local government may best operate some communication systems that support their own missions. However, many needs of society can be met by commercial ventures or individuals, and the quality and availability of communication services may be linked closely to the kinds of activity and the level of freedom granted to the service providers.

The national radiocommunications law should make provisions for public access to the spectrum management decision process and set requirements for government responses to public input. The specific processes whereby the public presents its spectrum requirements or its position on spectrum issues to the spectrum manager may be described elsewhere, but the right to access, and any limits to that access, could be established in the law. Based on the spectrum manager's mission to manage spectrum use in the national interest, responding to public input is essential. Therefore, the radiocommunications law should require the spectrum management authority to provide the public with information on its decisions, including written explanations of the basis for its decisions. In addition, the law should provide a process for review and appeal of decisions under established criteria and procedures.

The primary day-to-day tools of spectrum management are the set of published regulations and procedures promulgated and adopted by the national spectrum regulator. These regulations serve as the basis for the daily conduct of radiocommunications use and enable spectrum users to understand how their operations are governed. The regulations provide a method of interaction with the spectrum management authority. These regulations and procedures should cover areas such as procedures for obtaining and renewing a licence, emission standards, equipment authorization procedures, channelling plans, and operational requirements, as well as procedures for spectrum monitoring, inspection, and enforcement.

1.1.2 ITU rules, regulations and associated standards

The ITU has established general rules and regulations regarding international spectrum allocation and spectrum management which are contained in the Radio Regulations (RR) published by the ITU (http://www.itu.int/publ/R-REG-RR/en). Considering these international regulations, each member state creates its legislation and relevant rules and regulations to accommodate its national radiocommunication infrastructure and goals. These rules provide the necessary framework for the administration and enforcement of the spectrum management process including the authorization of equipment, based on specifications and standards for transmitter characteristics.

Adherence to such standards and specifications helps to ensure the interoperability of network components and seamless communication and data transfer between different networks.

The accreditation of devices and equipment ensures some degree of compatibility with the communications network. Specifications can also be modified in accordance with international standards, while considering any potential impact on the service providers networks.

It provides a competitive framework for manufacturers in line with the increasing requirements for access to the frequency spectrum.

1.1.3 Spectrum planning and allocation

Spectrum planning is the process of establishing priorities and protocol for the allocation of the radio frequency spectrum for new devices, services, or the expansion of existing services. Spectrum allocation involves making fundamental decisions on the long-term distribution of radio frequency spectrum among different radiocommunication services. Allocations are made on either an exclusive or shared basis and on either primary or secondary user principles. At the international level, this allocation is governed by World Radiocommunication Conferences (WRCs) and is reflected in RR Article **5**. Administrations can use the International Table of Frequency Allocations to establish their own national frequency allocation table, allocate frequency bands to radiocommunication services and authorize specific systems.

To use the spectrum efficiently, it is essential to allocate frequency bands that will meet the propagation requirements of the intended service. For example, services that are typically required to provide omni-directional coverage over a large area, such as broadcast television, are allocated frequency bands that are relatively low in the spectrum; private mobile radio (PMR) services are allocated VHF/UHF frequency bands to ensure limited local coverage; and for global aeronautical and maritime services, which require worldwide

coverage, HF frequency bands are allocated. These allocations are sometimes subdivided into channel plans to ensure that specific loading, and channel (and frequency) re-use requirements are met. Effective spectrum planning is key to ensuring that the needs of the existing services as well as anticipated needs for various radiocommunication services are met optimally.

In response to requests from particular users, administrations should follow these allocation tables to assign appropriate frequencies for the needed radio system, issue relevant licences and produce appropriate records in the database. Technical procedures of frequency assignment should allow effective channel and frequency re-use, based on permissible interference concepts or necessary frequency-distance separation criteria between radio networks.

Spectrum planning is the first process conducted by the Frequency Spectrum Regulatory Department resulting in balanced decisions expected to maximize effectiveness of all uses of the frequency spectrum, preserve bands for future growth, and satisfy economic goals.

Concluding regional and international border agreements to ensure the reuse of the frequency spectrum without harmful interference or distortion.

1.1.4 Spectrum engineering

Spectrum management involves the evaluation and analysis of emerging communication technology. Studies and field testing provide information to support decisions related to these new technologies. Though social, economic, and political issues are considered, decisions are usually based on engineering and technical factors. Therefore, a spectrum engineering function versed in these analysis techniques, and knowledgeable in technological developments, is needed to provide unbiased assessments to those within the policy and planning groups need to consider other factors such as economics and national policy. They may identify and recommend solutions to interference problems, determine technical characteristics necessary to ensure compatibility between systems, or encourage the use of alternative technologies. The use of engineering models supported by appropriate databases perform simulations to predict the impact of frequency assignments on the spectrum management plan. Models can be used to predict whether compliance with rules and regulations (e.g. satellite power flux-density limits) is possible, and to assess the potential for sharing by analysing the probability of interference.

To handle the growing volume of requests for radio frequency usage across various radio services, automation can be highly beneficial. By implementing predefined, radio-specific workflows, the decision-making process becomes more efficient, robust and transparent. Service-specific settings – such as selecting an appropriate wave propagation model and associated parameters – can be fixed and shared with all engineers to ensure consistent and expedited results.

1.1.5 Frequency coordination and notification

Considering that the radio spectrum is a limited resource and the demand from both private and government users continues to increase, it is imperative to create a mechanism for the assignment of radio spectrum to various services and systems while maximizing the number of users who can be accommodated. This is implemented through a frequency coordination process.

Frequency coordination is closely related to the frequency planning process as it relates to the harmonization of the use of radio spectrum with the aim of minimizing interference and maximizing the use frequencies between different systems and services. The process starts with the selection of frequencies for a system that is not likely to cause interference to other existing systems. This information can then be exchanged and "coordinated" at a local, regional, or international level to harmonize the use of frequencies and ensure compatibility between systems.

The frequency coordination process involves several key elements. First, an administration has to define the coordination procedures to support decision making. The procedures will define the information required for application, the criteria for evaluation of applications, the decision-making process and the method(s) of notification. Next, there has to be an exchange of information between the applicant for a new service and the coordinators. The information should contain sufficient technical data to assure that the new service will not cause harmful interference and be compatible with existing services. The effectiveness of frequency

coordination is directly related to the accuracy and currency of the spectrum management database and the ability to accurately predict the interoperability of the proposed system with existing systems. Frequency coordination and compatibility studies between existing and proposed radio facilities is a necessary component of effective spectrum management.

International frequency coordination is a procedure that should be implemented before giving a frequency assignment to a station that might conflict with that of another country. This frequency coordination procedure is usually under a special agreement concluded between two or more countries as described in Recommendation ITU-R SM.1049. Global, general rules for the assignment and use of frequencies and special agreements are described in RR Articles **4** to **9** and **11**.

1.1.6 Licensing, assignment and billing

Frequency licensing is another important process of spectrum management concerned with the conditional authorization given to entities or individuals to use a frequency or frequency band(s) for a specific purpose. Frequency assignment refers to the authorization of the use of a frequency or frequencies within allocated bands. The necessary administrative steps in the process of licensing and frequency assignment are defined by the applicable rules and regulations within an administration. Typically, a government agency administers the licensing function or process. Once the agency has determined that the proposed communication system complies with these rules, authorization is granted through the issuance of a licence. If any significant changes are made to a licensed system, rules usually require the user to notify the regulatory agency of these changes so that a revised license may be issued. If these procedures for licensing are followed, they will ensure that the integrity of the spectrum management database is maintained by promptly reflecting changes made in operational systems. Data on decommissioned systems can be temporarily moved to an inactive section of the spectrum management database for future reference and eventual removal.

The licensing and administrative functions of spectrum management have benefits that go beyond merely creating and maintaining a spectrum management database of technical parameters. The licensing process can be a source of revenue for the administration in the form of fees when the initial licence is granted, and fees for renewal of existing licenses. It can also be a source of revenue as part of the enforcement process through fines and penalties for operating without a proper licence, operating outside of the licensed parameters, or operating in defiance of the established rules and regulations.

1.1.7 Spectrum monitoring

Spectrum monitoring is one of the key components of spectrum management that involves the observation and analysis of the radio frequency spectrum providing information on the status of its usage. It is performed with tools, procedures and processes that ensure the frequency spectrum is free from interference, and services are operating with the required quality. Monitoring may also detect the use of sub-standard devices and equipment that may cause degradation in performance or harmful interference.

Spectrum monitoring is carried out remotely using fixed, transportable and mobile stations, as well as portable hand-held measuring equipment, without necessarily informing the owner or user of the monitored radio equipment of this action. As a result, monitoring makes it possible to determine only those technical and/or operational characteristics of the monitored radio equipment that are somehow related to its emission.

Moreover, not all parameters related to radio emissions can be determined directly through monitoring. For example, licensed parameters of radio transmission equipment such as the power of the transmitter, as well as the height and gain of its antenna. This is because the field strength measured at the receiving point of the monitoring station, among other conditions, is a combination of all these three parameters and it is impossible to subdivide the influence of each of them separately. All characteristics that are subject to monitoring are described in this Handbook.

The purpose of spectrum monitoring is to support efficient spectrum management in general, including frequency assignment, planning and licensing functions while minimizing interference.

Spectrum monitoring information is necessary in practice because the authorized use of the spectrum may be different from the actual usage. This may be from misuse due to the complexity of the equipment, interaction with other equipment, a malfunction of equipment, unauthorized use or deliberate misuse.

The use of the spectrum occurs around the clock throughout the year, whether locally, regionally or globally hence spectrum monitoring should also be continuous if the purposes and goals of monitoring are to be appropriately fulfilled.

An important role of spectrum monitoring services is to investigate, monitor and address excessive uses of the operational capacity of frequency bands and channels, measuring the intensity of the electromagnetic field and submitting it in accordance with the recommendations of the World Health Organization.

The growing adoption of automated spectrum monitoring systems has proven to significantly improve the efficiency, accuracy and reliability of data collection and analysis. Integrated platforms that consolidate monitoring results from multiple stations, automate data validation, and generate unified reports allow administrations to optimize human and technical resources. These systems facilitate early detection of potential interference, ensure consistent data processing, and support data-driven decision-making. Automation of monitoring also enables personnel to focus on more strategic analytical tasks, thereby improving the overall capacity and effectiveness of spectrum management.

The monitoring results can serve as a trigger for inspection.

1.1.8 Inspection of radio installations

The inspection of radio installations is an effective means of periodically assessing user's operational parameters and ensuring more efficient use of the spectrum because it aims to verify that radio stations are installed and operating in accordance with their assigned technical parameters. The inspection involves the physical visits to the installations and recording of the observed operating parameters and may involve validation of the results with on-site measurements.

Unlike spectrum monitoring, inspection is carried out directly at the site where the radio equipment is installed with the possible connection of measuring equipment to the feeder of the radio transmitter or to the emitting element of the ISM installation. Appropriate couplers should be used to make connections to feeders of powerful transmitters. Based on the results of measurements, a detailed survey of the inspected equipment and a study of the relevant documentation, it is possible to obtain comprehensive information on all technical and operational characteristics of this equipment.

In some cases, for example, when measuring the power of the transmitter, measurements by connecting measuring equipment to the transmitter feeder cannot be performed. This may be due to the physical inability to provide access to the feeder, the absence of an appropriate power meter or a feeder connection element. In such cases, indirect power assessment has to be carried out remotely, but at close range, using field strength monitoring facilities with subsequent calculations, as described in Report ITU-R SM.2156.

The operating parameters of a station are important in preventing interference, thereby allowing multiple stations to co-exist on the same frequencies and/or in the same geographic areas and are useful in ensuring the efficient use of the spectrum. The parameters are important in determining a station's coverage area and the amount of spectrum occupied. Stations that operate outside their authorized parameters have a great potential for causing interference to other spectrum users and will impact new authorizations on co-channel and adjacent channel frequencies.

Several different approaches may be taken by administrations in the planning and implementing inspections of radio facilities. These approaches may include:

– regular, periodic inspection of all stations;
– initial inspection of all newly authorized installations;
– remedial inspections based on triggers (for example, increased number of interference reports, or discovery of rule infractions);
– the inspection of a percentage of all stations;
– inspection based on statistical methods; and
– inspections based on risks.

An example of an effective approach is to inspect a percentage, or "sample" of existing authorized facilities/transmitters. The facilities included in the sample could be selected randomly for different services.

The information obtained during inspections supplements spectrum monitoring information and is compared with the authorized operating parameters to determine compliance to the license conditions. The compliance level of the sample provides an estimated measure of overall compliance with national regulations. In subsequent years, the sample sizes and service categories of facilities subject to inspections may be adjusted based on the compliance results of the previous year. In other words, if compliance were relatively high in a particular service, the number of samples could be reduced; alternatively, if compliance were low, a larger sample of a particular service could be undertaken.

A more detailed discussion of inspection techniques, statistical sampling determination, equipment for inspections and detailed inspection procedures can be found in the latest version of Report ITU-R SM.2130.

1.1.9 Law enforcement

The benefits of spectrum management cannot be realized if the users fail to comply with the conditions of their licence(s) and the appropriate regulations. National laws, rules and regulations should include provisions defining the actions that can be taken if a user is found to be non-compliant. Based upon the severity of the violations, enforcement actions could be taken ranging from issuance of warnings, imposition of fines (penalty), licence revocation, terminating operation of systems and undertaking legal prosecution, in accordance with the national laws. Without effective enforcement procedures, the integrity of the spectrum management process would be compromised. The ability of an administration to enforce established rules and regulations about the operation of radiocommunication systems is dependent upon effective spectrum management, spectrum monitoring and radio station inspection. When a complaint concerning interference is received, then through monitoring the location of the interfering signal can be determined along with the transmission type and other technical parameters that may aid identifying the source. Moreover, the spectrum management database can be searched to determine if the source of interference is a licensed transmitter operating outside of its authorized technical parameters or is from an illegal operator, allowing for further investigation.

1.2 Spectrum management considerations

As discussed in § 1.1.7, spectrum monitoring can support the process of spectrum management. Below are some of the considerations of spectrum management.

1.2.1 Efficient use of spectrum

The rapid growth of demand for worldwide communication services, driven by the emerging information-based society, could lead to a shortage of available spectrum unless measures are taken to manage the spectrum on national, regional and international levels. Because frequency spectrum is a limited resource, required growth should be achieved through effective management and efficient use of the available spectrum.

Efficient use is achieved by strategically allocating portions of the spectrum to meet the requirements of users while minimizing waste of the spectrum. Conservation of spectrum will enable future growth and the emergence of new wireless technologies.

1.2.2 Spectrum sharing

The ability of one or more users or services to share a segment of the frequency spectrum without interference is an important consideration in spectrum management. Sharing of spectrum effectively increases the amount of spectrum available for the wide variety of services. Spectrum sharing can be facilitated by:

– power control;

– geographical separation of users;

– separation of radiation patterns;

– time separation of users;

– permitting tolerable interference without becoming harmful;

– use of newer technologies that allow the coexistence of multiple transmissions on the same frequency.

It can take place at different levels:

– among different radio communication services or applications, whether at international level for services with a global footprint (satellite, aeronautical, maritime), based on provisions in the Radio Regulations and coordination of frequency assignments, or at national level;

– among different entities or type of users (e.g. governmental versus commercial use);

– among different licensed users of the same/similar application (e.g. PMR services, Point-to-point links);

– between protected primary users and licence-exempt users (e.g. radars and EESS versus 5 GHz RLANs);

– between different licence-exempt users.

Efficient sharing requires good coordination between national bodies that manage the use of spectrum and may also require coordination between administrations at the international level near country borders. Allocation of spectrum to users with geographical restrictions takes advantage of the limitations of signal propagation. The simplest example of geographical restrictions is the differences in allocations between the ITU Regions. On a smaller scale, geographical separation is also the basis of frequency planning for a cellular system, which allows for frequency re-use after an appropriate physical separation between cells and their associated emission patterns have been achieved.

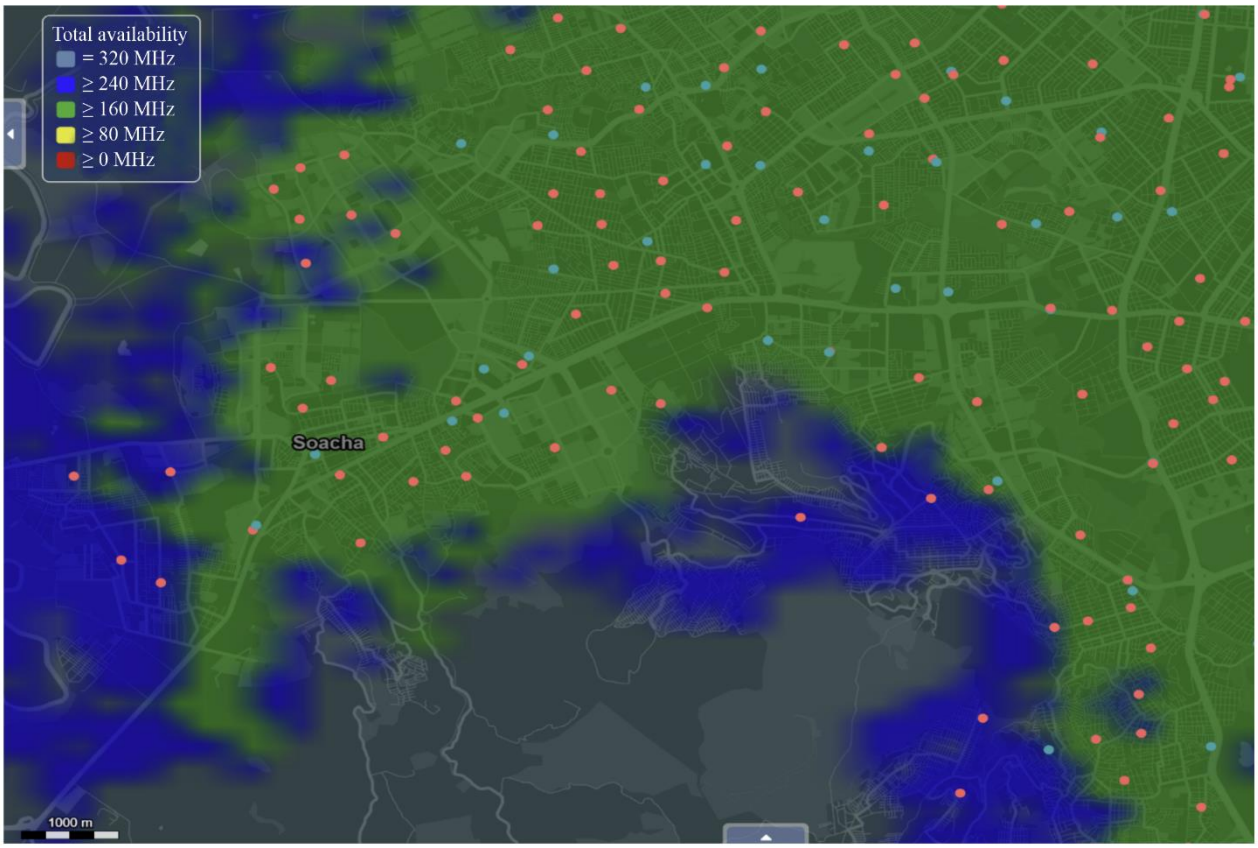
Time separation is also an effective method of facilitating sharing using time-agile technologies and trunking systems. In these systems, one or more channels may be shared by many users that have delineated transmission time requirements. Many systems are capable of coexisting in the same time and space segment of the spectrum, depending upon the specific modulation and interference threshold or multiple access scheme of each system (e.g. code division multiple access (CDMA)). For example, one of the primary advantages of spread spectrum technology is its increased resistance to interference. This characteristic allows multiple transmissions to occupy the same spectrum at the same time without disruption but, of course, within system limitations.

Likewise, estimates of spectrum availability derived from coverage or spectrum utilization maps (based on geographic area, technologies, and operators) make it possible to visualize the utilization of frequency blocks via heatmaps at national, regional, and local levels. Such information can be useful in estimating the availability of contiguous spectrum in specific areas. While such data can support decisions related to frequency availability, it is not conclusive, hence it is necessary to also consider frequency assignment and licensing data.

Figure 1-2 illustrates spectrum availability in the 3.5 GHz band within a region where a total 320 MHz has been allocated to mobile network operators (80 MHz per operator) for 5G cellular service. In the Figure, areas where 240 MHz is available, indicating utilization by a single operator, are shown in ice blue, while areas where 160 MHz is available, indicating usage by two operators are shown in green. The dots in the Figure denote the locations of stations belonging to mobile network operators, each represented by a different colour.

FIGURE 1-2

Spectrum availability map



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Report ITU-R SM.2404 provides additional information on the methods of sharing at both authorization and allocation level. An important requirement for the implementation of spectrum sharing is infrastructure sharing which aid the reduction of the number of sites and environment footprints. The possible options of shared use of spectrum and telecommunication infrastructure (network sharing) that might be implemented by Member States are set out below:

– passive infrastructure sharing of physical elements such as masts, containers, towers, power supply, generators, inter-site communications, fibre optic cables and air conditioning equipment; and

– active infrastructure sharing (of radio access network (RAN) elements such as antenna, base transceiver station (BTS) and radio network controller (RNC).

Network sharing can lead to cost reductions for network deployment and operation, increases in the quality and availability of telecommunication services, as well as to increased competition and lowering of tariffs for telecommunication services.

Recommendation ITU-T D.264 and the Output Report on ITU-D Question 4/1 (Study period 2018-2021, revision 2025) provide additional information on infrastructure sharing.

1.2.3 Economic aspects

Radiocommunications have become an increasingly vital part of the telecommunications infrastructure and economy of a country thus making economic approaches to national spectrum management essential. These approaches promote economic, technical and administrative efficiency, and help ensure that radio services are able to operate on a non-interference basis. To have effective radiocommunications, a country requires effective spectrum management.

The starting point for an effective spectrum management is to obtain adequate financial resources. These resources can be obtained from the administration or from fees collected from the use of the radio spectrum.

The fees can vary from processing of a single radio licence to the auctioning of large portions of the radio spectrum. Rational and balanced fees can promote the efficient use of the spectrum, provided they incorporate the right economic incentives. They should not be so low as to be negligible in the eyes of spectrum users or so high as to exceed market value such that the spectrum may be idle and generate no revenue or benefits.

In Chapter 2 of Report ITU-R SM.2012-6 (06/2018) – *Economic aspects of spectrum management*, on Strategies for spectrum financing mechanisms, one of the legal principles states that "It is therefore lawful for the authorities to require, moreover, that private spectrum occupants also pay *administrative fees* (known also as frequency management fees or service fees, as well as *administrative charges* or, where there is no ambiguity, simply as *charges*) to cover all of the costs arising out of spectrum planning, management and monitoring activities." It also states that "The establishment of spectrum fees and administrative fees must be carried out with due respect for the rules of transparency, objectivity, proportionality and non-discrimination." Moreover, "Where transparency is concerned, it is particularly important that the rules governing the establishment of fees be simple and readily understandable by all concerned." Administrations may adopt the principle that the beneficiary pays the administrative costs. Cost based fees (charges) may apply.

Auctions may be most appropriate when there are competing applicants for the same frequency assignment (see Chapter 8 'Monitoring system planning and tenders'). Auction revenues may vastly exceed spectrum management costs but the auction approach holds potential for an accurate reflection of the market value of the spectrum. Auctions may not be appropriate for wireless services in which there is limited competition for spectrum assignments, for socially needed services such as first-responders (firefighters, paramedics, police officers and the emergency phone number, available everywhere free of charge in the EU 112 and the North American E911) safety and national defence, and for some other specific services, e.g. international satellite services. Since recent auctions have placed significant values on spectrum, sometimes in the billions of dollars, administrations should ensure that an auctioned spectrum band is acceptable for use, whether by moving existing users or through the implementation of sharing conditions. Monitoring such bands in the appropriate coverage areas will support this activity.

Several administrations have implemented various forms of support for national spectrum managers. These include:

– communication groups with a direct interest in spectrum such as advisory committees, trade associations, professional organizations, and quasi-governmental associations;

– frequency coordinators and designated spectrum managers;

– spectrum management consultants, and support contractors.

These supporting methods have the potential for conserving government financial or human resources, increasing the efficiency of spectrum use, improving the efficiency of frequency assignment and coordination, and supplementing the expertise of the national spectrum manager.

For additional details on spectrum economics and efficiency, see Reports ITU-R SM.2012 and ITU-R SM.2523.

The economic aspects of developing the spectrum management system and monitoring subsystem are described in detail in Chapter 8 and Recommendation ITU-R SM.1392.

1.3 Spectrum monitoring goals

The purpose of spectrum monitoring, as previously described, is to provide information on the status of spectrum usage to the spectrum management process. The goals of spectrum monitoring are described below.

1.3.1 Monitoring for compliance with national rules

One of the goals of spectrum monitoring is to identify those transmissions that do not conform to requirements either because the transmission is unlicensed or because of some technical non-compliance of the transmission with national rules and regulations.

There are several reasons for this type of work:

– an unauthorized or defective transmission causes interference leading to poor services for other users;

– unauthorized transmissions represent loss of licence income to the administration, a disincentive for other users to seek licences, and they complicate the resolution of interference;

– planning can only effectively proceed in a stable and coordinated environment;

– the public has a right to an acceptable level of quality of broadcast, mobile radio and paging services.

1.3.1.1 Verification of technical and operational parameters

Monitoring is used to obtain detailed information on the technical and/or operational characteristics of radio systems that can be received remotely by analysing relevant emissions. This might typically include a detailed measurement of the emitted spectrum of a transmitter and/or its antenna pattern by using measuring equipment mounted on platforms such a helicopter or a drone. These measurements can provide information needed in a particular electromagnetic compatibility (EMC) analysis, to verify conformance with the characteristics authorized in a particular frequency assignment record or as part of a type-acceptance process to ensure that a particular kind of equipment will operate compatibly with other equipment in the concerned frequency band. Finally, measurements might be made to ascertain that a given transmitter is operating within specified limits.

Important information can be obtained by analysing the emission spectrum of a signal from the monitored radio equipment at the point of reception using a monitoring station. A measurement technique related to the spectrum should be selected that will allow various types of signal modulation to be quantitatively measured in a useful way. Thus, a measurement system should have a variety of bandwidths, filters, attenuators and other elements that may be selected and adjusted individually for the signal being measured. Vector signal analysis capabilities are required for some of these measurements.

1.3.1.2 Resolution of interference

Spectrum monitoring data is useful in detecting, identifying and resolving the cause of interference to authorized transmitters enabling the radio services and stations to coexist compatibly. This can also reduce the resources associated with installing and operating these telecommunication services while providing economic benefit to a country's infrastructure with interference- free, accessible telecommunication services. Spectrum measurements may detect the presence of radio frequency energy causing the interference. This energy could be in the form of:

– unauthorized transmitters;

– intermodulation distortion resulting from a combination of transmitters and unintended spurious emissions;

– emissions from non-communication devices such as lighting, construction equipment;

– intentional jamming devices.

Although a wide variety of spectrum measurements combined with engineering analyses may be needed to resolve some types of interference, spectrum monitoring data often plays a key role. Aural monitoring will often be useful in learning the identity of transmitters involved in the interference. More detailed information on the resolution of interference is provided in § 2.3.4.1.

1.3.1.3 Detection and identification of unauthorized transmitters

Detection of unauthorized transmitters is challenging as they are often operated adjacent to licenced services in crowded bands. In this case, it can be difficult to separate unauthorized signals from those that are licenced, especially when the transmitters share frequency band and have similar modulation characteristics. Real-time spectrum analysis can be a useful tool to visualize the presence of an unauthorized transmitter in a densely packed band of licensed transmitters.

Detection of unauthorized signals can also be accomplished by aural monitoring on frequencies where authorized users have complained of interference or where frequency assignment records show no legally-assigned users. Direction finding and information derived from aural monitoring can help identify and locate illegal transmitters after their operation has been detected.

1.3.2 Monitoring to aid spectrum management policy

Effective spectrum management is only possible when the planners are adequately informed on the current usage of the spectrum in various dimensions such as frequency, time and location and the trends in demand. While much data is collected from prospective users on licence applications or renewal forms, it is seldom adequate for spectrum management purposes. These records only indicate that the use of a frequency is authorized but may not provide adequate information on whether or how the frequency is to be used. Therefore, a frequency band that appears heavily used based on frequency assignment records may or may not be so.

Currently, in many countries there is a direct connection between the spectrum management and monitoring systems, with automation to schedule monitoring tasks and to store the monitoring results in a central database. This setup provides frequency planners with immediate access to monitoring data, while monitoring staff can access the licensing database in real time, leading to more efficient work processes. The following sections describe the ways in which spectrum monitoring can support the implementation of national spectrum management policies.

1.3.2.1 Provision of spectrum usage (occupancy) data

Spectrum occupancy data is derived from measurements of how often a frequency or frequency band has a signal(s) present (exceeding a power level) during a specified observation interval. Measurements on a single frequency can reveal usage patterns over a twenty-four (24) hour period (including busy hour and hours of peak, average and minimum usage) as well as on a monthly, quarterly or yearly basis. Combining data from many frequencies can show the usage across a band, or for a selected group of users.

Channel occupancy and band congestion information is valuable for several spectrum management. For example, it can be used to identify vacant channels in a band or to prohibit the addition of more assignments to heavily used channels. Such data can also be used as a trigger for an investigation to be conducted, either when signals are present on unassigned channels, according to the frequency management records, or when no usage is seen on frequencies with assignments. Changes in time-of-occupancy statistics in a specific geographical area, can reveal trends that can assist with the re-allocation of vacant bands when the existing bands become too crowded.

Occupancy measurements are particularly helpful in the land mobile radio bands or similarly channelized communication bands. Expectations for occupancy (e.g. minimum, average, maximum) could be established by the spectrum management process for reference purposes for each of the services involved.

The relationship between monitoring information and spectrum management records is not always straightforward. While occupancy information indicate that a frequency is in use, it does not provide the identity of the transmitter. The detection of a signal on a frequency does not necessarily mean that the signal originated from the assigned transmitter. Identifying the actual transmitter may require additional actions such as technical identification, aural monitoring for call signs or direction finding (see Recommendation ITU-R SM.1600). In addition, the absence of a signal during the measuring period does not necessarily indicate the absence of a frequency assignment or that the frequency is unused as an assigned transmitter may have been inactive at that time. More information on measurements of channel occupancy can be found in Report ITU-R SM.2256.

1.3.2.2 An aid to new assignments

The use of frequencies by each licensee varies according to business need, time of day and the day of the week. License data can be used to predict usage, but the accuracy depends on the sophistication of the prediction model and the quality of the supporting data. As congestion increases, monitoring data obtained from the geographical area of the proposed new assignment will be invaluable for the identification of a frequency (or frequencies) most suited to the purpose.

1.3.2.3 An aid to developing better management models

Monitoring data may be expensive to collect and analyse. Therefore, it is impractical to utilize monitoring data for all assignments. Areas with light radio activity may be adequately served by modelling based only on the available licence data. Monitoring data collected in busier, more congested areas can be compared to the levels

predicted by the model with the results used to identify suspect licensing data, and then to refine the model to best fit the real radio environment. This approach helps validate the model and subsequently makes it more effective. Accordingly, monitoring is best focused on those congested areas most in need of regulatory attention and assistance.

1.3.2.4 An aid to dealing with complaints and queries

As congestion grows, the users will become less satisfied with the availability of a service or its quality. By monitoring areas with disproportionately large number of complaints, the true nature of a problem can be determined, and the best remedial action devised. It also helps substantiate or refute allegations regarding the perceived quality of service.

1.3.2.5 An aid to categorizing and interpreting interference and propagation effects

The VHF and UHF bands are not immune to the effects of anomalous propagation such as ducting. The result may be interference from services normally considered too distant to warrant great efforts in coordination.

These effects are typically short-lived and while statistical data on them may be available, it is only by monitoring that the implications can be accurately assessed. It may be that only a few services are affected by only a few distant transmitters. The appropriate cure will likely be case-specific. Persistent monitoring data across effected areas will greatly aid in identifying the causes of this type of a problem.

1.3.2.6 An aid to spectrum sharing

The increasing demand on the spectrum is driving the need for more services to share the same frequency band(s). Some service types are incompatible but often the decision to share involves trials to determine the degree of compatibility. Monitoring during the trials provide information such as relative signal levels, quality of service, occupancy, etc., that will aid analysis of the shared systems' compatibility.

1.3.2.7 Database verification and correction

The integrity of databases requires regular updates and verification. The data obtained on the use of spectrum through monitoring plays a crucial role in the verification of the accuracy of spectrum management databases and keeping them up to date.

1.4 Spectrum monitoring tasks

1.4.1 Tasks derived from the Radio Regulations

The following monitoring service tasks are derived from the Radio Regulations (RR):

– monitoring emissions for compliance with frequency assignment conditions;

– frequency band observations and frequency channel occupancy measurements;

– investigating cases of interference;

– identifying and stopping unauthorized emissions.

The regular monitoring of emissions for compliance with authorized conditions and subsequently eliminating non-compliant emissions helps to prevent radio interference. Technical parameters such as frequency, bandwidth, power levels, frequency deviation, class of emission, and – with certain radiocommunication services – communications content needs to be periodically measured for compliance. For example, amateur radio communications should be monitored to ensure that call signs are regularly used, and no broadcasts are made in amateur bands.

Frequency band observations aim to determine who uses which frequencies/channels, as well as when and how they are utilized. Channel occupancy measurements aim to determine the degree to which frequencies are used and when hence, which frequencies are unused, and may involve the identification of emissions and their basic technical characteristics. The knowledge of the actual use of spectrum is essential for deciding whether a certain frequency can be assigned to additional users. These data also form the basis for national and international frequency coordination. In view of the increasing role played by radio applications in every area of life, swiftly and effectively investigating and eliminating radio interference is a task of economic

importance. Special priority should be given to eliminating interference to safety services such as the aeronautical, police and fire services.

While stopping unauthorized emissions aims primarily at preventing radio interference, it can also protect income, since fees are paid only by authorized frequency users.

1.4.2 Tasks on a national basis

In additional to the tasks indicated in § 1.4.1, the monitoring service is often charged with tasks not directly derived from the RR such as:

– assistance on special occasions such as major sporting events and state visits;
– radio coverage measurements and verification of planning criteria (see Recommendation ITU-R SM.1875);
– radio compatibility and EMC studies;
– technical and scientific studies;
– ensuring reliable communications on sensitive sites;
– monitoring wireless applications like Wireless Power Transmission (WPT);
– technical support and field advice to spectrum management departments.

During state visits, Formula One races, and other special events, large numbers of diverse radio equipment are used within a confined space. The users are often not aware that they need a frequency assignment or that they may not be able to use certain frequencies in different countries. In the interest of preventing interference and responding immediately should interference occur; it is expedient for the monitoring service to be on site to monitor spectrum use and act swiftly to investigate and eliminate any interference. Crucial for success is planning and the timely coordination with the organizers and the staff responsible for frequency assignment, who also need to be on site to assign frequencies at short notice when necessary. Examples of spectrum management and monitoring during major events can be found in the Report ITU-R SM.2257.

Many administrations also consider radio coverage measurements and verification of planning criteria as the responsibility of the monitoring service. This involves measuring field strength and, in some cases, quality parameters such as bit error rate (BER) and adjacent channel power in many locations. However, other Administrations see such measurements as the task of the radio network operators and not the monitoring service, as the market guarantees sufficient radio coverage quality.

Before frequencies are allocated for a new radio application, compatibility with existing radio systems needs to be ensured. Purely theoretical radio compatibility studies are often not adequate. The monitoring service may often be called upon to assist with the necessary practical studies if it has the required measurement equipment and expertise. It may likewise be called upon to assist in certain scientific studies such as long-term observations of propagation conditions.

The monitoring service can also be involved in the protection of critical communications on sensitive sites as military facilities, airports, or national borders, where spectrum monitoring is crucial to ensure that such facilities remain free of interference. Furthermore, the monitoring service can also be called upon to provide radioelectric surveillance in areas where open competitive examinations take place for the recruitment in the public sector, during which mobile communications are not allowed and signal jamming in the relevant frequency bands may be needed.

Sometimes technical expertise may be needed to measure and evaluate new types of equipment being proposed for use in local networks. Such evaluations involve detecting the technical characteristics (frequency, power level emitted, etc.) and are needed to assure that the new equipment can be operated without causing interference.

1.4.3 Co-operation of radio monitoring and inspection services

It is important that the monitoring service effectively support the inspection service to ensure that spectrum is used properly and efficiently. The following tasks are usually assigned to the radio inspection service:

– inspecting radio equipment on site;

– measuring electromagnetic radiation from radio equipment to rule out health hazards;
– processing cases of electromagnetic compatibility (EMC) related to non-radio equipment;
– market surveillance activities when radio equipment or other electronic equipment is introduced to the market.

Regarding market surveillance, radio and telecommunications equipment used worldwide is required to respect regional or national requirements to ensure they are operating in compliance with relevant technical regulations or restrictions (frequency band, power levels, etc.).

Failure to respect these regulations and restrictions creates a risk that the equipment will cause harmful interference. Therefore, administrations may want to use market surveillance to evaluate the quality of the radio products in use. Typically, random product samples are obtained in retail stores and then tested in the administration's testing laboratories or an independent private test laboratory under contract with the administration.

Regardless of whether the radio monitoring and inspection services are part of the same unit, they should cooperate closely and have access to a common license database where essential monitoring information such as transmission power, centre frequency and authorized bandwidth is stored. In searching for sources of harmful interference, it is helpful for the monitoring service to also have details of the radio equipment which the inspection service has found to be non-compliant. Conversely, the monitoring service can trigger inspections by recording the same parameters that would be recorded during an inspection. Monitoring results obtained in this way can be used to select candidate radio stations for on-site inspections. This in turn may substantially reduce the number of on-site inspections needed.

Monitoring can further support the radio inspection service by determining if a faulty radio station has already been repaired and preventing the inspection service from having to re-inspect the equipment on site.

The monitoring service has high measurement equipment costs compared to the inspection service. Hence many administrations select fewer locations for the monitoring service than for the inspection service. Since the inspection service is usually based closer to user radio stations, they can complete the final investigation of interference cases which were initiated with direction finders at fixed monitoring stations.

1.4.4 Co-operation of radio monitoring with other bodies

The monitoring services in most countries do not have any law enforcement powers, hence cooperation with the police and judicial system is therefore essential for confiscating illegal transmitters and imposing penalties for violations of conditions. Experience shows that it is helpful if the police and the courts are familiar with the major provisions of telecommunications law.

1.4.5 Measurement tasks and essential equipment

To carry out the tasks mentioned in § 1.4.1, the monitoring service equipment should be capable of measuring:

– centre frequency;
– field strength and/or power-flux density at fixed points;
– occupied bandwidth;
– modulation characteristics;
– spectrum occupancy;
– out of band emissions;
– polarization;
– direction finding and emitter location.

To perform the measurements described above, measurement equipment and tools are required including:

– omnidirectional antennas;
– directional antennas;
– monitoring receivers;
– spectrum analysers;

– direction finders;
– emitter location systems;
– I/Q and spectrum recorders;
– vector signal or modulation analysers;
– decoding equipment or software;
– signal generators.

It should be noted that modern measurement equipment can often fulfil more than one function, and be packaged in very portable, even handheld formats. Many measurement functions can also be realised in software operating on I/Q files made in situ.

For the measurement of space emissions, more complex equipment and antenna systems, may be needed due to the path loss and time dependency based on the varying position of the satellite relative to the monitoring location.

Chapters 3 to 5 of this Handbook contain detailed information on the measurements, methods and equipment.

1.5 Relationship between spectrum monitoring and spectrum management

The functions of spectrum monitoring and spectrum management are closely related. Monitoring data provides valuable information on spectrum usage to support planning, allocation, assignment and coordination, thus promoting more efficient use of the radio spectrum. The data is also used in the resolution of interference and supports regulatory enforcement against unauthorized users or violators of authorized conditions. Spectrum monitoring serves as the "eyes and ears" of the spectrum management process and provides a method of verification thus "closing the loop" in the spectrum management process.

Spectrum management provides data on:

– predictions of service coverage based on channel models;
– reference database of users (licensees);
– communications equipment information (RF power, occupied bandwidth); and
– radio station information (identification, coordinates, altitude above sea level, altitude above ground level, antenna gain, azimuth and elevation angles).

Spectrum management data may prioritize monitoring tasks according to importance (e.g. safety of life), communications policy, and interference complaints, while spectrum monitoring provides measurement data as elaborated in § 1.4.5.

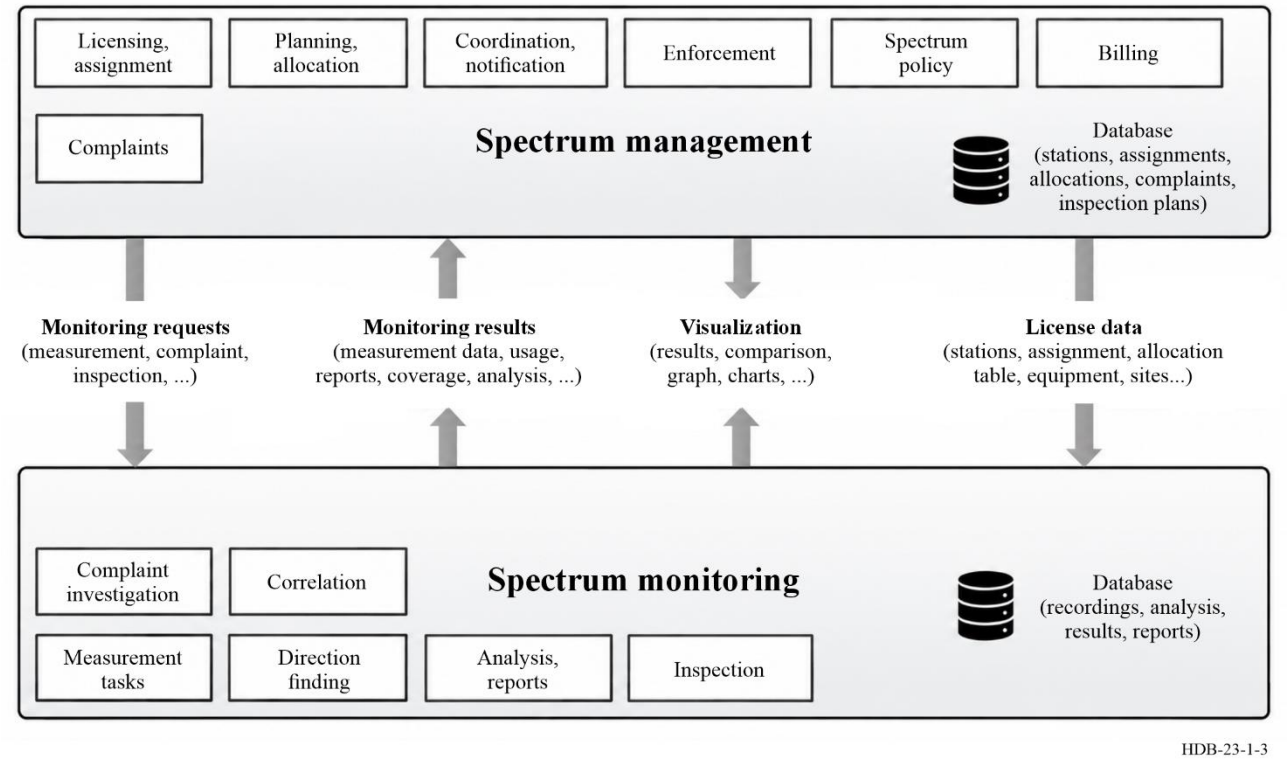
An integrated display (showing both management and monitoring information) allows the visualization and comparisons of the monitoring results with the licence data which aids the detection of infringements, discrepancies, and unauthorized stations. Generation of records, reports, and statistical data make it possible to perform analysis of different services, such as broadcasting, mobile, safety, and fixed services. Additionally, coverage predictions and quality of service measurements may be displayed together using data overlays on digital terrain mapping. The investigation into interference complaints, including identification and mitigation, is helped by using monitoring and management data together. Licence enforcement and band clearance may be necessary in the case of an unauthorized station that is causing harmful interference.

As illustrated in Fig. 1-3, an integral component of spectrum management is a database or databases for storage of the relevant operating parameters of radio communication facilities. These databases contain records of authorized users of the spectrum, radio communication stations and their assigned frequencies, locations, and emission parameters, which provide the necessary information for the administrative process and technical analysis supporting spectrum management. They also store information on licensing, billing, inspection and complaints. Without accurate and up-to-date database records, the integrity of the spectrum management process would be compromised. A monitoring database is a strategic tool for radio spectrum management, enabling the storage, organisation and analysis of radio spectrum measurement data. It brings valuable insights to inform plans for monitoring and spectrum measurements in different regions across a country.

Interaction between the spectrum management service and the monitoring service allows the bi-directional access to information to enable the correlation of licence data with real-world measurements which can assist in the identification of licence violations, illegal spectrum usage and interference. The overlay of information such as allocation plans on measurements, display of licensed stations on a map and access to relevant information regarding the license holder provide an additional layer of information for the greater understanding and verification of the measured signal environment as well as direction finding or geolocation results.

FIGURE 1-3

Interactions between spectrum management and monitoring



Recommendation ITU-R SM.1537 provides further details on an integrated and automated interconnection between spectrum management and spectrum monitoring systems.

Modern integrated spectrum management and monitoring systems now utilize software to automate data collection, processing, evaluation, and interference analysis tasks. More advanced software incorporates big data analytics, machine learning, and artificial intelligence for the integration and analysis of huge data sets from the management and monitoring systems. These systems provide insights on trends and patterns of how spectrum is used in various dimensions such as time, location, frequency, signal strength and services. They use real-time dashboards and intuitive maps to provide valuable insights that enhance spectrum management and decision making and are discussed in Report ITU-R SM.2542.

1.6 International monitoring

1.6.1 Centralising office and international cooperation

According to RR Articles **15** and **16**, each administration or common monitoring service established by two or more countries, or international organizations participating in the international monitoring system, shall designate a "centralising office" to which all requests for monitoring information shall be addressed and through which monitoring information will be forwarded to the Bureau or to other Administration's centralising offices. It is essential that Member States exercise the utmost goodwill and mutual assistance in the settlement of problems of harmful interference.

The centralising office staff therefore need to meet a number of basic requirements. The staff have to be authorized to issue direct instructions to the monitoring stations, be available around the clock, and be familiar with the monitoring station's essential working procedures and technical facilities.

If these requirements are met, it is irrelevant whether the centralising office belongs to a ministry or other organization or whether it forms part of a monitoring station.

Where practicable and subject to agreement by the administrations concerned, cases of harmful interference may be dealt with directly by their specially designated monitoring stations. Many European administrations endorse direct cooperation between the monitoring stations.

Annex 1 to Chapter 1 provides an example of an agreement that allows monitoring stations to request foreign monitoring stations to make measurements in cases of interference and to use their vehicles in the other country.

Cooperation and support are based on the principle of mutuality, and hence are free.

However, individual administrations may also have special facilities such as satellite monitoring stations which are extremely expensive. A contractual agreement may be concluded enabling other administrations to use such facilities against payment of the costs.

1.6.2 The international monitoring system

As indicated in this Handbook, the monitoring of emissions is an essential component of the frequency spectrum management process. Each country should operate monitoring facilities as essential tools to support efficient spectrum management at the national level. Additionally, some administrations have decided to cooperate in the development and operation of an international monitoring system and, to that end, have adopted regulatory provisions, as described in RR Article **16**. This is in support of the ITU-R goals to ensure efficient and economic use of the frequency spectrum and rapidly eliminate harmful interference.

The international monitoring system comprises only those monitoring stations that are designated as such by administrations. The stations may be operated by an administration, a public or private agency, a monitoring service established jointly by several countries or by an international organization. The responsible administrations determine whether the station's technical standards are in accordance with the relevant ITU-R Recommendations and communicate this information to the ITU.

In accordance with RR Article **20**, information on such stations is published by the ITU in the List of International Monitoring Stations (also known as List VIII), together with the names of the centralizing offices.

In addition, List VIII, includes information about the different functions each monitoring station can perform, both in the terrestrial and in the space radiocommunication services.

The ITU List VIII is an indispensable document for operating in the international monitoring system because the information it contains enables rapid contact to be made between centralizing offices, particularly in the case of harmful interference. Administrations should carefully update the information in List VIII and notify the Bureau immediately of any significant change. Up-to-date information contained in List VIII can be retrieved directly from the online database available on the ITU web site (https://www.itu.int/en/ITU-R/terrestrial/monitoring/listVIII/Pages/Internationalmonitoringstations.aspx), which includes important information on the procedure to update the List and where to find the associated publications.

1.6.3 Coordination role of the Bureau

The international monitoring system provides a means for coordinating monitoring activities to satisfy international needs relating to the collection, exchange and publication of monitoring data. Monitoring activities within the system are carried out in response to a request by either administrations or the Bureau. The Bureau plays an essential role in the operation of the system by coordinating the organization of regular and special monitoring programmes, collating and studying the results and making the necessary arrangements for communicating them to administrations. Since 1999, the Bureau has published the reports of monitoring data received from administrations on the ITU website) and the corresponding electronic files can be downloaded free of charge.

The Bureau organizes different types of monitoring programmes on a worldwide or regional basis, as well as limited programmes confined to a smaller area or a few administrations.

1.6.4 Use of international monitoring data by the Bureau

The Bureau needs monitoring data to perform the following tasks:

– assisting in the clearance of unauthorized or out-of-band operations;

– assist administrations in cases of harmful interference;

– guide administrations in selecting frequencies;

– prepare for Radiocommunication Conferences, in particular for allocating frequency bands, by providing reports on spectrum occupancy.

Because of the different effects of propagation in different parts of the frequency spectrum, the monitoring data used by the Bureau generally relates to terrestrial services in the frequency bands below 28 MHz or those used in space radiocommunications. In some cases, however, particularly when intervening in cases of interference, the Bureau shall be able to obtain data from any frequency band.

With the increasing use of the frequency spectrum by space radiocommunication services, there is a growing need for monitoring data from the bands used by these services. Recommendation **36 (Rev.WRC-19)** invites ITU-R to study and make recommendations concerning the facilities required to provide adequate coverage of the world to ensure efficient use of resources, and invites administrations:

– to make every effort to provide monitoring facilities as envisaged in RR Article **16**;

– to inform ITU-R of the extent to which they are prepared to cooperate in such monitoring programmes as may be requested by ITU-R;

– to consider the various aspects of monitoring emissions originating from space stations to enable the provisions of RR Articles **21** and **22** to be applied.

It is also essential that those administrations already having space monitoring facilities participate in the international monitoring system and to notify the Bureau of the particulars of their monitoring stations for inclusion in List VIII.

1.6.4.1 Assistance in the clearance of unauthorized or out-of-band operations

Periodically, the Bureau organizes special monitoring campaigns to identify unauthorized or out-of-band operations and encourage administrations to take the necessary action to eliminate the emissions concerned.

The frequency bands for which these campaigns are organized are usually those allocated to safety services. During these campaigns, the Bureau asks administrations to intensively monitor the concerned bands for a limited period (generally one week). The required data is detailed in a BR Circular Letter, and the Bureau summarizes the reports obtained for further analysis. If the Bureau determines with reasonable certainty that the unauthorized or out-of-band station is operating in the jurisdiction of a particular administration, it will notify the concerned administration of the reported operations and highlight the potential interference such emissions pose to safety services.

Interfering emissions are sometimes caused by spurious emissions resulting from maladjustment of a transmitter working in another band. They may also be caused by stations recorded in the Master International Frequency Register (Master Register) as operating on a “non-interference basis” as foreseen in RR No. **4.4**. Administrations are therefore generally able to clear the resulting interference.

For example, a special campaign has been ongoing since 1987, pursuant to Resolution **205 (Rev. WRC-19)** to identify the sources of unauthorized emissions in the frequency band 406-406.1 MHz, which is exclusively allocated to satellite emergency position-indicating radiobeacons. WRC-15 introduced additional protection measures for the adjacent bands 405.9-406.0 MHz and 406.1-406.2 MHz. Since 2018, the campaign has included the monitoring of the impact of unwanted emissions from systems operating in the frequency bands 405.9-406 MHz and 406.1-406.2 MHz on the mobile-satellite service reception in the frequency band 406-406.1 MHz. This campaign has produced very positive results. The number of interfering emissions that have been detected and mitigated have been published in the BR annual reports, and the reports are also

available on the ITU website under Activities on Resolution **205 (Rev.WRC-19)** Monitoring in the band 405.9-406.2 MHz.

1.6.4.2 Assistance to administrations in cases of harmful interference

Pursuant to RR Article **15**, an administration may request the assistance of the Bureau in solving cases of harmful interference. In the studies conducted for this purpose, the Bureau frequently uses data secured from international monitoring, often obtained by organizing special programmes involving only a few monitoring stations.

The Bureau may require two types of data in cases of harmful interference:

– The identification and location of possible sources of harmful interference. In this case, the Bureau will request administrations with monitoring stations suitably equipped and located to make the necessary observations and measurements.

– The Bureau evaluates the results to determine the location of the interfering stations and identify the administration under whose jurisdiction it appears to be operating. The administration responsible is approached to promptly eliminate the source(s) of the interference.

– The measurement of the field strength of the interfering station. This may be necessary when there is uncertainty as to the degree of harmful interference, or if a specific criteria in the RR or an ITU-R Recommendation, might apply. In this case the Bureau will, request the assistance of administrations whose monitoring stations are suitably located and equipped to make the necessary measurements.

1.6.4.3 Guidance to administrations in selecting frequencies

If requested by any administration under RR No. **7.6**, and particularly by an administration of a country in need of special assistance, the Bureau will use the information recorded in the Master Register, together with monitoring data received in the context of regular or special monitoring programmes, to identify potential frequencies that could be assigned to their stations in the fixed or mobile services.

Special attention will be given to cases where replacement frequencies are needed for the regular operation of stations in the aeronautical or maritime mobile service due to unresolved cases of harmful interference.

1.6.4.4 Preparation for radiocommunication conferences

As part of the preparations for a radiocommunication conference, particularly if the conference has to make decisions on changes in the Table of Frequency Allocations, the Bureau may organize special monitoring campaigns designed to supplement the data in the Master Register. Results would be reported to the conference in the form of a report so that it can evaluate the impact of the proposed changes in spectrum use.

In addition, a radiocommunication conference may request the Bureau to organise special monitoring campaigns not only to provide information concerning the use of a specific part of the spectrum but also to support studies concerning interference caused to safety communications for further analysis by a subsequent conference.

1.6.5 International monitoring programmes

1.6.5.1 The regular programme

Since the introduction of the Table of Frequency Allocations adopted by the Atlantic City Radio Conference in 1947, the ITU has maintained a regular programme of monitoring the HF bands between 2 850 and 28 000 kHz. The first issue of the "Summary of Monitoring Information" appeared in 1953, and these summaries have been published regularly since then. The main objectives of the regular monitoring programmes of the International Monitoring System can be summarized as follows:

– to assemble information on spectrum utilisation at the location of the monitoring stations and to derive insights on how the spectrum is being used;

– to identify stations whose emissions are not in conformity with the RR No. **16.8**;

– when requested, to assemble information on the use of the bands exclusively allocated to specific services (i.e. broadcasting, maritime, aeronautical) for consideration by appropriate, future radiocommunication conferences;

– to provide administrations, which do not have monitoring facilities, with information for frequency management purposes.

Several administrations normally contribute reports to the Bureau for the preparation of summaries of regular monitoring. The Bureau validates the information and compiles a database in the form of quarterly files, which are continuously updated and published on the ITU website under Regular Monitoring Program in frequency bands between 2 850 kHz and 28 000 kHz.

1.6.5.2 Special programmes

From time to time, the Bureau organizes special monitoring programmes covering certain frequency bands and time intervals. These are carried out over several two- to three-week periods, each near in time to at least one equinox and two solstices.

Each such special programme is announced in a Circular Letter sent to all administrations, inviting them to make all the necessary arrangements well in advance for effectively participating in the campaign. The Circular Letter also contains a list of the different parameters which the monitoring stations are invited to collect and indicates the format in which the data should be communicated to the Bureau.

1.6.6 Global monitoring coverage

One of the main conditions for the successful operation of the international monitoring system is to achieve uniform coverage of all parts of the world by monitoring stations adequately equipped and taking part in these ITU monitoring programmes.

Resolution ITU-R 23 refers to the need for extension of the international monitoring system to a worldwide scale, and resolved that:

– all administrations participating in the international monitoring system, including for monitoring of space station emission levels, should be urged to continue to do so to the maximum extent possible;

– administrations, which do not at present participate in the international monitoring system, should be urged to make monitoring facilities available to that system, in accordance with RR Article **16** using the relevant information contained in this Handbook;

– cooperation between monitoring stations of different administrations should be encouraged and improved with a view to exchanging monitoring information, including information related to space station emissions, and to settling harmful interference caused by transmitting stations that are difficult to identify or cannot be identified;

– administrations, located in those areas of the world where monitoring facilities are inadequate, should be urged to promote the establishment of monitoring stations for their own use and make them available for international monitoring, in accordance with RR Article **16**;

– data supplied by the monitoring stations participating in the international monitoring system may be used by the Bureau to prepare summaries of useful monitoring data in accordance with RR Article **16**;

– administrations with more advanced terrestrial and space monitoring systems should be urged to accept officials from other administrations to train them in the techniques of monitoring, direction finding and geolocation. Initial contact for training may be made to the appropriate centralizing office as incorporated in List VIII.

1.7 Collaboration among monitoring stations of different countries

As mentioned in § 1.6.6, one of the objectives of Resolution ITU-R 23 by the Radiocommunication Assembly is the cooperation between monitoring stations of different administrations. Different forms of cooperation can be envisaged, examples of which are described in §§ 1.7.1, 1.7.2 and 1.7.3. Recommendation ITU-R SM.1394 provides guidance on the requirements in setting up a Memorandum of Understanding between agreeing administrations regarding cooperation in spectrum monitoring matters.

1.7.1 Collaboration below 30 MHz

To avoid overlapping the activities of monitoring stations covering the same area, coordinated monitoring frequency plans can be organized so that they can all take part in a specific monitoring programme. For this purpose, the part of the spectrum to be monitored can be divided into sub-bands that each monitoring station will explore in accordance with a predetermined timetable (e.g. once a week). Some common operational rules should be defined to ensure a uniform method is used in conducting the operations, including the appraisal of reception quality. These operations should be coordinated by one of the participating monitoring stations.

These coordinated arrangements can be implemented temporarily, for instance during special monitoring programmes organized by the Bureau, or for more permanent monitoring requirements.

Another field of activity where close coordination between monitoring stations may be essential is the determination of the location of a transmitter and its identification, particularly in the case of harmful interference. In such cases the most important factors are the speed and accuracy of intervention. Administrative and operational arrangements should be concluded, a priori, among the administrations of the countries in which the monitoring stations are located. These stations can then quickly establish direct contact to perform simultaneous coordinated measurements of the same emission including, as necessary, taking bearings on the transmitter concerned.

One of the monitoring stations should take a leading role in the exercise but it does not need to be the same station in all cases. Normally, the station that requests the investigations would take the leading role.

1.7.2 Collaboration above 30 MHz

Neighbouring countries are increasingly endeavouring to provide harmonized radiocommunications by adopting common specifications to facilitate cross-border operations. This phenomenon is a very marked one, at least in Europe, and should encourage the countries concerned to set up harmonized or even integrated monitoring facilities by using identical procedures and, under certain circumstances, a common infrastructure. This would make monitoring services more efficient leading to lower and, therefore, more readily acceptable financial investments required for establishing and maintaining monitoring infrastructure.

Collaboration between technicians of different countries in the definition and development of a common operational system could also have a positive impact on technical innovation and the quality of inter-personal and related international relations.

As mentioned in § 2.5, countries should establish monitoring stations that are carefully sited, considering the typical range of transmitters. Locating the sources of harmful interference can be challenging and may require the radio monitoring services to use direction finder measurements to obtain accurate cross-bearings. To meet these requirements, it may be sometimes necessary to conduct some measurements from neighbouring countries. If the radio monitoring service detects interference originating across the border, crossing into the adjacent country may be required. In this context, a bilateral agreement between neighbouring countries on co-operation in the field of radio monitoring can expedite cross border movement thereby supporting effective direction-finding measurements, monitoring as well as interference resolution. Once the source of interference is identified as originating from across the border, the radio monitoring service of the relevant foreign Administration will be notified and will assume responsibility for further actions.

Neighbouring countries are advised to conclude special agreements based on RR Article **16**, to optimize the monitoring procedures and facilities to be established in border area(s). Such bilateral or even multilateral agreements may be classified into three categories.

The first category is the initial step while the second and third categories constitute longer-term objectives. The main issues to be covered are the following:

First category:

– cases in which the regional authorities on both sides of the border are authorized to enter into direct contact, for example, when the only frequencies concerned are the direct responsibility of the regional centre (frequencies to be specified), based on RR No. **16.3**;

– in such cases, methods for informing the centralizing offices (RR No. **16.3**);

– exchange of list of actions authorized by the regional authorities, e.g.:
  - carrying out measurements from their territory on transmitters in the neighbouring country, at its request, and providing the results to it;
  - authorizing a mobile team from the neighbouring country to come and take measurements;
  - mutual assistance in both cases.

Second category:

– joint establishment of a plan for the distribution of monitoring stations in border areas;

– definition of the interfaces to enable each country to take measurements of transmitters located on its territory from any station in the border area;

– establishment of a schedule for installing harmonized monitoring facilities.

Third category:

– exchange of lists of authorized transmitters in the border areas of each country, together with their technical characteristics, so that "foreign" transmitters are no longer regarded as unknown;

– exchange of such lists using automatic remote data transmission procedures.

Arrangements of this kind exist in many parts of the world, particularly in congested areas. The long-standing arrangements among Canada, Mexico and the USA constitute a typical example of such cooperation.

The need for such collaboration is also exigent in the European area where, for instance, France, Germany and Switzerland entered into an agreement of the first category in 1993. A detailed description of this arrangement, as well as a model agreement is presented in Annex 1 to this Chapter.

In developing its national spectrum monitoring system, France's aim is, in particular, to make access to its system easy and automatic, both for authorized national users and for users from agreeing countries.

1.7.3 Collaboration on the monitoring of space emissions

The set up and operations of satellite monitoring facilities is a very expensive affair due to the highly specialized and costly nature of satellite monitoring requirements. It is therefore suitable to establish a common approach to conduct space radio monitoring. One way to do so is through cooperation that provides the possibility for the administrations involved to access and undertake satellite monitoring activities.

An example of fruitful cooperation between administrations is the Memorandum of Understanding on Satellite Monitoring (SAT MoU), entered into force in 2003. The agreement provides the possibility for any Administration of the European Conference of Postal and Telecommunications (CEPT) to access and undertake satellite monitoring activities in the frequency band 130 MHz – 26.5 GHz and on the sharing of costs for administrations using these facilities. The agreement facilitates the following monitoring activities:

– investigation of interference to and from satellites;

– detection of the illicit use of satellites;

– monitoring the usage of spectrum and orbital resources.

Further details on the purpose and measurements activities carried on within the agreement is found in Report ITU-R SM.2453.

Cooperation agreements on space monitoring facilities are also in place between ITU and several administrations in accordance with Resolution 186 (Rev. Dubai, 2018) of the Plenipotentiary Conference (Dubai, 2018). Information about monitoring facilities set up by various telecommunication regulatory authorities for the monitoring of emissions from GSO and non-GSO space stations is found in the Report ITU-R SM.2182 together with their locations, capabilities and contact information.

The current map of the space monitoring facilities, as detailed in List VIII International Monitoring Stations and Report ITU-R SM.2182 as well as those in the Memoranda of Understanding (MoU) agreements between administrations and ITU, are available at https://www.itu.int/en/ITU-R/space/Pages/ITU-Space-RadioMonitoring.aspx.

Annex 1

to Chapter 1

Agreement, protocol and model cross border agreement for direct co-operation among radio monitoring stations

Agreement among the Administrations of France, Germany and Switzerland on the direct co-operation between radio monitoring stations

AGREEMENT

Among the signatory administrations on the direct co-operation between radio monitoring stations

The following has been determined by the signatory Administrations within the scope of their responsibilities as defined by Articles 20, 22 and 24 of the Radio Regulations[1] for the settlement of problems of harmful interference or unauthorized emissions:

1 If the assistance of another country is deemed necessary, the centralizing office of the country concerned shall turn to the centralizing office of the other country in accordance with the Radio Regulations (No. 1875 of the Radio Regulations).

2 The bodies responsible for radio monitoring shall designate radio monitoring stations which, when deemed appropriate, may establish direct contact with each other (Nos. 1946 and 1956 of the Radio Regulations).

3 The Administrations give their consent for mobile monitoring equipment of the radio monitoring stations mentioned in **2** above to cross the common borders of their countries in the fulfilment of radio monitoring tasks.

Consent from the other country is to be obtained in each case.

Stations may use their own monitoring equipment.

The use of means of communication is not covered by this Agreement.

4 No official acts may be performed directly towards citizens within the territory of the other country.

5 The radio monitoring stations shall mutually support each other in the application of this Agreement.

6 The bodies responsible for radio monitoring shall stipulate the terms regarding the application of this Agreement in a protocol.

Paris, 16 September, 1993	Bern, 15 October, 1993	Bonn, 9 November, 1993
For the Minister responsible for Telecommunications in France: The Director of the Réglementation Générale:	For the General Directorate of the Swiss PTT Operators: The Director of the Directorate for Radio and Television:	For the Federal Minister of Posts and Telecommunications:

[1] NOTE 1 – Replaced by Articles 16, 15, and 18, respectively.

PROTOCOL

Regarding the Agreement of 1993 among the Administrations of Germany, Switzerland and France on the direct co-operation between radio monitoring stations

1 Participants in the co-operation

– for Germany: the radio monitoring stations in Constance and Darmstadt;

– for France: the *services régionaux des radiocommunications* of Lyon-St André de Corcy and Nancy and the international radio monitoring centre in Rambouillet;

– for Switzerland: the radio monitoring stations in Basel, Bern, Châtonnaye, Geneva, St. Gallen and Zürich.

2 Form of the co-operation

The direct co-operation provides for the following possibilities for the countries participating in the Agreement:

– to carry out measurements with fixed and mobile monitoring equipment at the request of a neighbouring country on their own territory;

– to carry out measurements with their own mobile monitoring equipment outside their territory;

– to exchange measurement results.

3 Procedure for the co-operation

The request for measurements shall be transmitted among the monitoring stations by telephone, by fax or by telex. If measurements with mobile monitoring equipment have to be carried out on foreign territory, a distance of 50 km from the border may not be exceeded.

4 Limits of the co-operation

The direct co-operation of the monitoring stations shall end when the request can no longer be treated on the grounds that the matter lies outside the competence of the monitoring station.

It shall also end

– when the measurements with fixed monitoring equipment are expected to require more than three hours;

– when the measurements with mobile monitoring equipment are expected to require more than nine hours or more than one monitoring vehicle.

In both cases, the requests are to be addressed to the centralizing office.

Paris, 16 September, 1993	Bern, 15 October, 1993	Mainz, 29 November, 1993
For the Direction de la Réglementation Générale; Le Service National des Radiocommunications:	For the General Directorate of the Swiss PTT Operators; Directorate for Radio and Television Department for the State Radiocommunications Monopoly:	For the BAPT; The Centralizing Office of the Radio Monitoring Service:

NOTE – Due to reorganisation of regulatory authorities, the name of the signing authorities have changed. Nevertheless, the agreement is still in use.

MODEL CROSS BORDER AGREEMENT

MODEL "CROSS-BORDER AGREEMENT ON RADIO MONITORING"

Agreement between (*Country A*) and (*Country B*) on radio monitoring for direct co-operation between (*Administration A*) and (*Administration B*) in cases when cross-border monitoring measurements by one of the Administration is necessary.

1 Objectives

In order to reduce the response time and to offer mutual help in cases of interference related to the tasks, it is agreed that (*Administration A*) and (*Administration B*) can make direct contact to assist each other and that the appropriate service of both Administrations can cross the common border to perform monitoring measurements by vehicle, using their own apparatus on the other side of the common border.

2 Scope

Either Administration can directly ask the other Administration to carry out fixed or mobile monitoring measurements in case of interference and in cases related to frequency co-ordination. This implies that for each monitoring measuring campaign the executing Administration shall report (e.g. letter or fax) to the other Administration on the measurements carried out.

3 Limitations

a) The direct co-operation ceases when the object of the request exceeds the competence of the Administration that has been asked to assist. In these cases the competent services have to be consulted.

b) It should be recognised that other tasks of the Administration involved may have higher priority than the need of the requesting Administration.

c) The direct co-operation also ceases when the distance from the border exceeds [the distance in km to be inserted].

d) Apart from the distance limitation imposed it is also forbidden to take enforcement actions under the host country's legislation.

e) The duration of the monitoring measurements is limited to [....(hours)].

4 Reporting

The monitoring measurements report shall contain at least the following data:

- time of the measurement(s) (UTC);
- place(s) of the measurement(s) (with GPS);
- the route of measurement;
- equipment used;
- values measured, frequency, level (dBuV/m), duration of occupation.

If the content of the radiocommunication is revealed through the monitoring measurements, the Administration who is involved with the monitoring measurements is obliged to consider this information as strictly confidential.

5 Copy of the Cross-Border Agreement

A copy of the Cross-Border Agreement on Radio Monitoring shall be kept in the measuring vehicles.

6 Reports

A report of the results of the measuring campaign should be addressed to the Administrations involved.

7 Contact Administrations

Both Administrations should indicate in the Agreement which telephone/fax/E-mail address can be used in the following situations:

- During office hours.
- Outside office hours.
- To send the reports.

8 Signatures of Administrations

Administration A: Administration B:

References

NOTE – In every case the latest edition of the texts should be used.

ITU Resolutions

Resolution ITU-R 23 – Extension of the international monitoring system to a worldwide scale

Resolution ITU-D 9 – Participation of countries, particularly developing countries, in spectrum management

ITU-R Handbooks

Handbook on National Spectrum Management

Computer-Aided Techniques for Spectrum Management (CAT)

ITU-R Recommendations

Recommendation ITU-R SM.1049 – *A method of spectrum management to be used for aiding frequency assignment for terrestrial services in border areas*

Recommendation ITU-R SM.1392 – *Essential requirements for a spectrum monitoring system for developing countries*

Recommendation ITU-R SM.1394 – *Common format for memorandum of understanding between the agreeing countries regarding cooperation in spectrum monitoring matters*

Recommendation ITU-R SM.1537 – *Automation and integration of spectrum monitoring systems with automated spectrum management*

Recommendation ITU-R SM.1600 – *Technical identification of digital signals*

Recommendation ITU-R SM.1875 – *DVB-T/T2 coverage measurements and verification of planning criteria*

ITU-T Recommendations

Recommendation ITU-T D.264 – *Shared uses of telecommunication infrastructure as possible methods for enhancing the efficiency of telecommunications*

ITU-R Reports

Report ITU-R SM.2012 – *Economic aspects of spectrum management*

Report ITU-R SM.2015 – *Methods for determining national long-term strategies for spectrum utilization*

Report ITU-R SM.2093 – *Guidance on the regulatory framework for national spectrum management*

Report ITU-R SM.2130 – *Inspection of radio stations*

Report ITU-R SM.2156 –*The role of spectrum monitoring in support of inspections*

Report ITU-R SM.2180 – *Impact of industrial, scientific and medical (ISM) equipment on radiocommunication services*

Report ITU-R SM.2182 – *Measurement facilities available for the measurement of emissions from both GSO and non-GSO space stations*

Report ITU-R SM.2256 – *Spectrum occupancy measurement and evaluation*

Report ITU-R SM.2257 – *Spectrum management and monitoring during major events*

Report ITU-R SM.2404 – *Regulatory tools to support enhanced shared use of the spectrum*

Report ITU-R SM.2453 – *Cooperation in the field of space radio monitoring*

Report ITU-R SM.2523 – *Assessment of spectrum efficiency and economic value*

Report ITU-R SM.2542 – *Next generation monitoring-proactive, autonomous and data driven*

Additional ITU-R texts

List VIII – List of International Monitoring Stations

ITU Operational Bulletin – Supplements to List VIII

Other References

CEPT/ERC/REC 01-09 E – *Model cross border agreement on radio monitoring" to assist a better co-operation on spectrum monitoring*.

CHAPTER 2

Organization, Physical Structures and Personnel

TABLE OF CONTENTS

Page

2.1 Introduction 35

2.2 Organization of the monitoring service 35

2.2.1 Organizational structure 35

2.2.2 Geographic deployment of monitoring stations 36

2.3 Monitoring operations and processes 37

2.3.1 Instructions and forms 38

2.3.2 Schedules 38

2.3.3 Case documentation 39

2.3.4 Typical administrative procedures 40

2.4 Support management system 47

2.4.1 Database 48

2.4.2 Reporting system, statistical analyses 48

2.4.3 Working plan 49

2.4.4 Resource planning 49

2.5 Siting, buildings, facilities 50

2.5.1 Siting of monitoring stations 50

2.5.2 Buildings and auxiliary facilities 56

2.5.3 Sources of interference affecting the operation of monitoring stations 65

2.5.4 Site survey 66

Annex 1 to Section 2.5 – Site survey checklist 67

Comprehensive evaluation report 71

2.6 Personnel 71

2.6.1 General 71

2.6.2 Categories of personnel 71

2.6.3 Training 72

Page

Annex 1 to Section 2.6 – Aspects of spectrum monitoring training..... 76

References 78

2.1 Introduction

This chapter describes organizational, administrative and personnel aspects of establishing and operating a monitoring service. Procedures needed to receive and act on complaints related to interference are discussed along with procedures needed for maintenance, repair and calibration of station equipment. Documentation and database forms are also described. It discusses physical considerations of the monitoring service such as proper siting of stations to have the most impact, the functional aspects of designing and implementing buildings for fixed stations.

The different categories of personnel needed for the operation of a monitoring service are also described together with their training requirements.

Detailed descriptions of different types of monitoring stations and equipment can be found in Chapter 3.

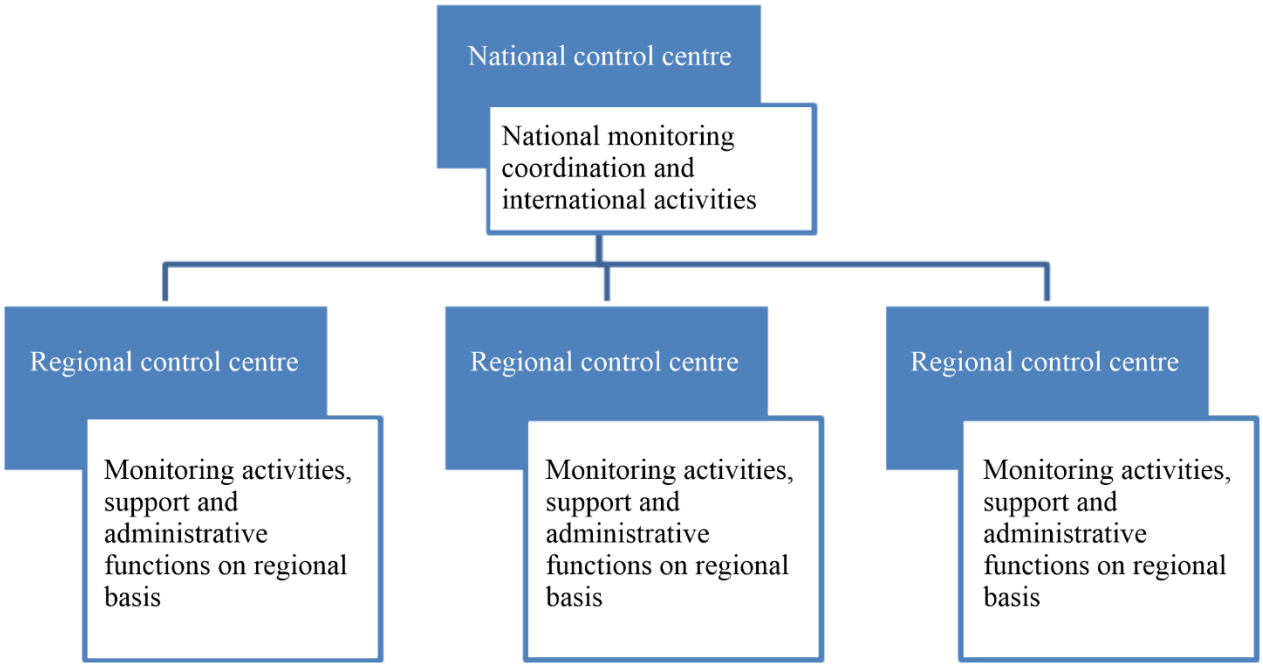
2.2 Organization of the monitoring service

2.2.1 Organizational structure

A monitoring service can be structured in different ways but is always impacted by the number and types of monitoring stations and by the Administration's organization (see Fig. 2-1).

FIGURE 2-1

Monitoring service organization structure



HDB-23-2-1

This section relates to manned monitoring stations which are assumed to have access to remote-controlled and mobile facilities. Subordinate monitoring stations may be remote controlled.

The management of the whole monitoring service at the top level (sometimes called the National Control Centre) defines the monitoring station's tasks and provides the necessary resources for operation. In some countries, Regional Control Centres are responsible only for defined regions. Their resources may include manned, remote-controlled, mobile, and portable monitoring stations. The Regional Control Centre should be

co-located with a manned monitoring station. Special monitoring tasks could be assigned to only one Regional Control Centre to satisfy nationwide requirements.

Regional control centres should be responsible also of administrative functions on regional basis such as the management of interference complaints received from operators located within the region. They should also maintain and regularly update a database containing information as spectrum occupancy and measurements. Such information can be used for a comparison with authorised parameters and should be part of a general database which can be consulted by officers of other regional control centres and of the national control centre.

Coordination between regional control centres should also be implemented to deal with interference issues involving different regions.

The centralising office (see § 1.6.1) may be assigned either to the National Control Centre or to one of the Regional Control Centres. The inspection service may be a separate organization, although it has proved expedient to integrate any co-located monitoring and inspection services. Furthermore, the centralising office or even the whole radio monitoring service may be part of the frequency management department.

The National Control Centre should also coordinate the international monitoring activities, such as management of monitoring tasks of national monitoring stations being part of the International Monitoring System (IMS). It should also cooperate with other administrations on international frequency coordination issues.

2.2.2 Geographic deployment of monitoring stations

The number of monitoring stations in a country depends on the density of radio services, required spectrum monitoring tasks, the geography, and not least, the financial resources.

It is unrealistic to think that absolute control of all emissions within any large area can be achieved or continuously maintained. This is why spectrum monitoring data will be in some cases statistical in nature, describing a limited sampling, limited geographically, in the time, frequency and signal level domains.

The following sections provide additional thoughts on the deployment of monitoring stations taking account of the different frequency ranges. The planning and optimization of spectrum monitoring networks is described in Report ITU-R SM.2356 and in § 7.8.

2.2.2.1 HF range and below

The use of HF frequency bands has been decreasing in the past few years for a number of reasons and thus the interest in maintaining monitoring fixed stations that operate below VHF, especially due to the large size of the antenna systems that may be required to enable the monitoring station to perform tasks such as long-range emission location those transmitted by ionospheric propagation effects.

Due to the large size of the antenna systems and increasing difficulties posed by the omnipresent manmade radio noise, such as produced by LED illumination and switched power supplies, large HF stations are usually placed outside urban areas, which poses other challenges related to infrastructure, security and human labour to keep the station operational.

Still, monitoring of frequency bands of HF and below may be of interest due to strategic and security reasons, especially considering that these bands still an important asset for backup and emergency system used by marine and other services that need to maintain long range communications.

Administrations maintaining spectrum monitoring services at these bands may keep only one station to cover areas that can reach up to hundreds of square kilometres and still provide acceptable location accuracy.

Administrations operating few fixed monitoring stations for HF for long range measurement, may not be able to precisely locate emitters, requiring on site measurements with active and magnetic field antennas, either portable, hand-held or installed on vehicles, to enable the last mile location of the emitters.

Even for administrations that are unable to maintain a fixed monitoring station network capable of operating in frequencies below 30 MHz, it’s advisable to maintain some portable/transportable/mobile equipment to enable the spectrum monitoring services to answer possible requests within these bands.

2.2.2.2 VHF/UHF range

Considering the limited range of VHF/UHF transmissions, monitoring stations should be located near to areas with high radio activity, where there is high potential for interference and recurrent demands for spectrum monitoring services.

A regional spectrum monitoring centre may control multiple direction finders and/or TDOA sensors to enable continuous surveillance of the spectrum usage over large areas.

Such monitoring centre may also include field teams equipped with transportable, mobile and/or portable equipment to cover an action area of several hundred kilometres, in accordance with the logistics within the service region. The area covered by field teams will be dependent on the available transport means, the geographical relief, the road network conditions, and the road traffic specific to some regions and of the urban areas.

Any areas not covered by fixed direction finders or TDOA sensors should be covered by mobile stations. The mobile teams should have the appropriate means to conduct the interference search and coordination with the adjacent region or county to make measurements at the borders.

Similar to the case discussed for HF, well equipped and trained field teams are essential to solve interference cases, cease unauthorized emissions, and fulfil other regular demands for monitoring services. On the other hand, fixed monitoring stations and sensors are required to enable continuous surveillance over critical areas, enabling faster and proactive response from field teams. The balance between both manual and automated strategies is a matter of debate within each administration policy towards spectrum management.

2.2.2.3 SHF and above

Deployment of fixed monitoring stations to cover SHF range and above has limited benefit due to path loss, directionality, the need for line of sight (LOS) and other factors associated with signals in higher band (higher modulation BW, lower power and coverage, etc.). Therefore, mobile, transportable or man-portable equipment are primarily used to perform spectrum monitoring tasks in such frequency ranges.

It is desirable that the regional monitoring centres maintain the necessary equipment and include adequate field teams to carry out monitoring activities in these frequencies within their geographical area of responsibility.

As detailed in Chapter 3, a wide range of different choices in terms of mobile and transportable monitoring stations can be considered depending on the specific tasks and requirements. An efficient planning of the available equipment in each regional monitoring centre is necessary, taking into account both the geographical size to be covered and the estimated most frequent activities to be performed in that area.

2.2.2.4 Satellite signals

Rapid growth in the number of satellites launched into space implies an increased risk of interference. Thus, administrations and regulators may wish to deploy and operate stations within their own territory to monitor space signals.

Satellite monitoring facilities usually require large spaces and should preferably be located outside urban areas in sites with a broad geostationary arc visibility for monitoring GSO satellites and horizon visibility for non-GSO satellites.

Well trained field personnel are also essential to operate space monitoring stations given the large range of space services, their rapid evolution in the recent years, and the complex equipment required for measurement.

Due to the highly specialised equipment and personnel required, as well as the stringent requirements for siting, deployment of satellite monitoring facilities may be expensive and technically difficult. Consequently, monitoring stations are currently operating in a limited number of countries and, as detailed in § 1.7.3 and Report ITU-R SM.2182, close cooperation between administrations is crucial.

2.3 Monitoring operations and processes

This section describes processes relating to planning, scheduling, performing, and maintaining terrestrial monitoring services, covering the tasks set out in § 1.4 using stationary, remotely controlled, and mobile measuring equipment. In view of the expense of radio monitoring systems and considering that radio

monitoring services are usually funded by taxes or fees paid by license holders, there is a need to organise and optimize the operations for efficiency and traceability. Hence, the management should document its strategies, systems, programmes, procedures, and instructions to the extent necessary to ensure the quality of the whole monitoring service. This should be communicated, understood and available to the appropriate personnel inside and outside of the monitoring service.

2.3.1 Instructions and forms

For routine tasks, instructions describing workflows, rights, and obligations for standard procedures should be established. Such instructions serve as reference material for both new and experienced staff.

In drawing up such instructions, a pragmatic approach should be adopted to ensure unambiguous and easily comprehensible guidelines, motivating staff by giving them a certain degree of leverage for individual decisions in accordance with the reproducibility requirements for each task, e.g. while in one hand, interference hunting is mostly investigative in nature and requires greater flexibility and experience, on the other hand, parametric measurements to ensure assert conformance to the licensed conditions should follow very strict and reproducible procedures.

Obviously, the degree of detail will depend on the qualification of the staff and the complexity of the regulatory requirements in individual countries. Separate instructions should be compiled for specific cases and special tasks not described in the standard instructions.

Digital or printed forms serve as useful aids when dealing with routine matters or tasks by ensuring uniformity and clarity. They should be structured logically and provide sufficient space for detailed notes. For example, the form used for registering interference complaints received by telephone should enable staff to ask for all necessary details. Here again, special cases may be reported requiring information not covered by the form. It is therefore important to provide sufficient space in the form to record further information.

Instructions should include a reference to the applicable safety regulations or quotations thereof. Taking care of the monitoring service personnel's health and safety is an important management task.

2.3.2 Schedules

Monitoring tasks can be split into stationary and mobile measurements with the following distinctions:

– scheduled tasks which cannot be postponed;
– scheduled tasks which can be postponed;
– unforeseen tasks which can be postponed;
– unforeseen tasks requiring immediate action.

The first category covers tasks such as field strength measurements, needed by the frequency administration by a certain date for licensing or international coordination purposes. Routine measurements such as general measurements verifying adherence to assignment conditions are not normally subject to a deadline and may therefore be postponed. The third category includes non-critical interference reports such as Citizen Band (CB) or amateur service interference. If, however, safety-related services such as COSPAS/SARSAT, or police radio are affected, immediate action is required.

The human and technical resources needed to address the tasks should then be assessed and coordinated. The schedule should be compiled and published as early as possible for staff to be adequately prepared. In case of urgent interference reports, the schedule has to be modified on short notice. This also applies in the case of essential personnel illness or unavailability of required equipment.

When planning and scheduling monitoring tasks, attention should also be paid to the following:

– If large areas need to be covered, it may be expedient for mobile measurement teams to remain in the area and be accommodated in a hotel rather than returning daily to avoid costly and unproductive time on road travel.
– The availability of the monitoring service should be ensured around the clock since interference may also occur at night. In some countries, monitoring stations are staffed 24 h/day, in others availability is assured either by round-the-clock staffing of a single monitoring station or by automatic call

forwarding to staff on call at home. However, availability does not only imply being reachable over the telephone: it is not sufficient to staff a monitoring service with one only person who would be unable to conduct urgent field work as the station would then be left unmanned.

– Vehicles and equipment need to be maintained on a regular basis or may require unexpected repairs, which means that they will be temporarily taken out of service.

– Regular staff meetings are essential to brief staff about any organizational changes or changes and developments in services, frequency assignments or regulatory matters. Such meetings also offer the opportunity to instruct staff on new radio technologies, licenses, and monitoring equipment (if no other training arrangements, e.g. by manufacturers, are foreseen).

These considerations also apply to the task of performing on-site inspection; thus, it is advisable to plan the work of monitoring and inspection together during the same visit. The schedule should be shown in a form allowing each staff member to identify who will conduct each task, locations for each task, the vehicle(s) to be used, and communication plan to maintain radio contact during the operation. A computer system to which all staff members have access is the most effective way to keep the schedule, but a simple notice board, or blackboard are good alternatives which function well.

2.3.3 Case documentation

Many engineers and technicians view measurements as their primary obligation and consider the associated documentation as a job of secondary importance. It is therefore essential to repeatedly stress the high value of complete and accurate documentation as an essential part of the staff's responsibility. If at any time doubts arise as to the reliability of measurement values, these doubts can only be dispelled by submitting a complete set of documentation proving the validity of the values.

The specific documentation for each case needs to be detailed enough to allow the reproducibility of the procedures adopted by any interested parties. As such, its complexity is directly proportional to the flexibility of the adopted measurement and investigative procedures.

Example: The quantified measured input power value is only meaningful if antenna height, terrain profile and range from emitter to monitoring receiver, bandwidth, type of detector, measurement location, antenna and k factor, and the setting of any attenuators are also known.

The documentation serves as a reference for future measurements, offers lessons to prevent interference, and provides a history of measurement data for the management information system (see § 2.4).

From the above, it follows that the documentation should comprise the following items:

– task number;

– task content;

– steps and techniques used to accomplish the task;

– entity requesting the task or source of interference complaint;

– staff involved in the task;

– date(s) and time(s) at which the task was carried out;

– precise measurement locations (e.g. coordinates);

– measurement equipment and antennas used (serial number or inventory number should be indicated to be able to determine whether the equipment was calibrated at the time it was used);

– chosen settings (e.g. attenuator activated);

– measurement set-up (block diagram, sketch);

– measured values (with units!) of frequency, bandwidth, power flux-density (or field-strength), bearings, etc. and observations, e.g. call signs and violations;

– any measurement protocols, spectrum analyser plots, data files, etc.;

– environmental conditions possibly affecting the measurement accuracy;

– vehicle(s) used;

– records such as videos, audios, and photos.

Signature or the author's initials should confirm the correctness of the data in the work report. Depending on the type of task, the documentation should also include a summary of the conclusions, decisions, recommendations, further action taken and associated reports.

Detailed guidelines for case documentation involving stations of the International Monitoring System can be found in Recommendation ITU-R SM.1139 (Annex 1).

2.3.4 Typical administrative procedures

2.3.4.1 Procedures for responding to interference complaints

Interference processing is not only the most important task, but also a very complex task, justifying a detailed description of the procedures involved.

FIGURE 2-2

Interference processing workflow

2.3.4.1.1 Receiving interference complaints

Interference is normally reported by telephone, chat, on-line forms, or email. The operator should inquire about the details and complete the interference report form. The key information needed includes:

– name, address, telephone/mobile number, and email address of the party experiencing the interference;

– data about the interfered-with device: frequency, type, coordinates, location, license number and other relevant data;

– timing of the interference (when first noticed, time, regular or sporadic, duration);

– description of the interference (humming, hissing, loss or degradation of service, etc.);

– suspected source of interference and details of any special events in the immediate area of the interference.

This information is essential to collect whether it is a case of interference which needs to be dealt with by the monitoring service or is merely an equipment fault involved, in which case the operator of the equipment or a repair service ought to be called in. Moreover, from this information the operator should readily identify already known issues and, in such a case, promptly inform the interference reporter that the interference is already under investigation.

2.3.4.1.2 Preliminary diagnosis and localization of the source of the emission

The priority assigned to the case depends on the interfered-with service and the number of interfered-with devices. The description of the interference will be used to decide on the procedure and measurements required to solve the interference. Other operators of the same radio frequency in the nearby area may be asked if they are also interfered.

Many operators of different services (e.g. satellite, broadcasting, mobile, fixed) have their own monitoring equipment to assess the quality of service. The Administration may use this infrastructure and advanced self-monitoring, to assist the interfered party. The interfered site may be best suited to monitor the interference considering its location, altitude above ground/sea level of the antenna.

As a rule, fixed and remotely controlled measurement equipment should be used to ascertain whether the interference can also be received and analysed at a monitoring station. Using AoA or TDoA means, it may be possible to roughly locate source of the interference. Location combined with other signal features such as modulation and bandwidth can limit the possible interference sources to relatively few with the help of frequency assignment databases. The operators of the suspected interference sources are contacted and asked about a change in their activities and to switch off their transmitter for a short time. This procedure is repeated until a change in the interference or spectrum clearly identifies the actual source. This approach is the most efficient way of identifying, locating, and eliminating interference.

If the source of the interference cannot be determined as described above, it will be necessary to deploy monitoring vehicles equipped with direction finders or TDoA sensors. Especially in the case of sporadic interference or interference to cellular operators, localization efforts may prove to be very time-consuming.

2.3.4.1.3 Measurement of emissions and possible interference sources

Once the source or interfering emission has been localised and identified, the technical characteristics responsible for the interference should be measured to determine the nature of the interference, i.e. whether the case involves co-channel interference, adjacent channel interference, receiver intermodulation, receiver saturation, conducted interference, or electromagnetic noise. During these measurements, the equipment used, and their settings should be recorded accurately to verify whether the interfering system/device is being operated in violation of the frequency assignment conditions or exceeds license threshold values. National standards and recommendations contain detailed equipment specifications and associated measurement procedures for a wide range of technical parameters that can help determine license compliance.

2.3.4.1.4 Measurement evaluation and follow-on actions

The measurement results should subsequently be compared with the frequency licence, assignment conditions or relevant standards. Depending on the outcome, the interfering system or device may either need to be taken out of operation altogether or its operation modified, or the system or device may have to be rectified, or the interference may have to be accepted. In many countries, the outcome will determine whether a fine or other penalty is payable.

National regulations, which vary from one country to another, specify whether the measurement team or another entity within the Administration is responsible for actions such as law enforcement to be taken. The requisite actions should not only conform to the law but also be reasonable. If a defective relay contact in a heating system turns out to be the cause for minor interference, it would be inappropriate in winter to demand that the system be shut down immediately. Instead, a reasonable period should be specified for eliminating the defect.

Special provisions apply to cases of interference involving foreign stations. In this connection, reference is made to RR Article **15** (Interferences), RR No. **16.3,** RR Appendix **10** (Report of harmful interference) and Report ITU-R SM.2181. It may also be expedient to specify procedures to be adopted in cases where military stations are involved.

2.3.4.1.5 Final check-up

In many cases, the monitoring service will be able to check whether remedial action has been taken using fixed or remotely controlled equipment. Where this is not possible, an on-site inspection may be necessary. The simplest way of dealing with the matter is by asking the interfered-with party whether the interference has

stopped. In some cases, subsequent periodic checks may be carried out to verify that the remedial actions to the interference have remained stable over time.

2.3.4.2 Procedures for identification and disconnection of unauthorised transmissions

Transmitters operated without the prescribed license or frequency assignment are potential sources of interference and must be taken out of service. Locating such transmitters may be initiated by any of the following:

– observation of such a transmitter by the monitoring service during routine measurements;
– interference complaints;
– other indications.

The initial steps taken are identical to those in interference processing. Information should be gathered about the transmitter through the evaluation of the measurement results. Since the operators of pirate radio stations are normally aware that they are violating the law, they will make every effort to remain undiscovered. They may employ the following tactics:

– incorrect and misleading data about the transmitter location including camouflage;
– remote operation of the transmitter;
– misrepresentation and disinformation;
– sporadic, irregular emissions;
– use of different frequencies;
– change of location.

Compared with "normal" interference cases, these tactics make it more difficult to localise and identify the transmitter. The monitoring service should adapt to the circumstances and take appropriate measures, such as extracting and evaluating message content. For example, monitoring operators involved in the identification of illegal transmitters should usually use, as much as possible, not dedicated vehicles and small-size equipment since there is the need to not make them recognizable during such activities. Details, which may first appear irrelevant, could assist to identify the illegal station and initiate a legal action.

Another difference is that the operator of an interfering station is usually keen on eliminating the interference and will therefore be willing to help solve the problem. However, operators of pirate radio stations are unlikely to cooperate in view of the consequences of their behaviour (penalty and confiscation of their equipment). It is therefore important for the monitoring service to collect unambiguous proof that can be used in court as evidence to support the claim of unlawful transmissions by the defendant. Seizure of the equipment during an actual transmission obviously constitutes irrefutable proof of illegal use; such an action, however, is contingent upon close coordination with the police.

The chances of being successful in combating the operation of pirate radio stations depends entirely on the legal framework in each country which should provide the basis for prosecuting the operators of such transmitters and confiscating their equipment.

2.3.4.3 Procedures for maintenance, calibration, and repair

This section describes procedures and methods to enhance the availability of the monitoring station, equipment, and the overall monitoring system. It describes the required support activities and tools needed for long-term reliable operation of the monitoring system.

The verification of station operability may consider the following strategies:

– periodic use of a built-in test (BIT) to detect failures of the station elements;
– scheduled preventive maintenance, enhanced functional tests and update activities to be done at defined intervals (i.e. monthly and yearly) to verify and maintain the station long term operability;
– calibration, at regular intervals, by comparison with standards and known reference signals to assert possible drifts in measurement results, introducing errors and/or uncertainties;
– repair and adjustments when a failure is detected should be rectified.

Other important issues are discussed at the end of this section including spare parts stock that should be available for a quick repair, software maintenance, and management of the system maintenance.

2.3.4.3.1 General considerations

Information on measurement accuracy depends on knowledge of the measurement uncertainties in the equipment and methods applied.

The accuracy required for a specific measurement is based on national and international standards and/or specified by the Administrations within the definitions of the spectrum monitoring service.

During normal use, measuring equipment is exposed to many environmental and operational conditions that can influence and alter its performance over time. Regular examination, maintenance, and calibration of the measuring equipment is therefore essential.

If the equipment is not regularly maintained, the probability of erroneous measurements and outages increases. If the measured values fall outside permissible tolerances, the measuring equipment is to be promptly tagged and taken out of service for repair.

When an item of equipment is brought into use, a file should be established immediately comprising documentation relating to purchase, warranty, maintenance, calibration and repair. This equipment file should be linked to the equipment using a unique reference identifier such as the serial or inventory number.

Records of all repairs and calibrations for each item of equipment should be kept in the files, to create a life history for each item. Labels should be attached to the equipment clearly stating its unique reference i.d. and may also be used to identify the equipment operational calibration condition in accordance with the administration's operational procedures, stating for example, the most recent date of calibration, calibration certificate number, and the next recommended calibration date.

In principle, calibration is periodically required for any measurement equipment. As detailed in § 2.3.4.3.4, the calibration rate depends on the equipment characteristics, the conditions in which it is kept/used, and the accuracy required by the adopted procedures. The complexity of the calibration procedure may also vary according to the intended use of the equipment.

In case that one instrument is found to be out of calibration, all the work done since the end of the previous calibration cycle needs to be reviewed, thus the need for periodic tests and evaluations performed between scheduled calibration events.

To ensure quality and compliance of measuring equipment with respect to specified accuracy, a multi-stage procedure comprising the following checks is proposed:

– basic functional test before and after each measurement campaign;

– enhanced functional test at regular intervals;

– maintenance at regular intervals by specially trained staff;

– calibration at predefined intervals.

Test schedules and testing intervals to be laid down for each individual stage are essential for such a quality system and should be laid down for each of the described stages.

These schedules should include details of the measuring equipment data and reference information, including the technical parameters to be tested, their nominal values, tolerances, and a checklist with instructions for carrying out the tests.

For the purposes of quality assurance, a staff member should be designated as having responsibility for quality whose tasks comprise in particular:

– maintaining a manual in which the procedures for maintenance and calibration are defined;

– ensuring that the test and maintenance schedules for each item of measuring equipment are drawn up and made available;

– monitoring compliance with the deadlines for testing, maintenance, and calibration activities.

Test report format should be defined within the test procedure associated with each measuring equipment or system. Such form should include reference to the methods applied, identification of the measurement system, test date and tester's name.

2.3.4.3.2 Functional test procedures

2.3.4.3.2.1 Basic

The basic functional test is directly related to each specific measurement task and can be carried out by the measurement staff themselves at the beginning and end of each measurement campaign or series of measurements.

Only those technical parameters that are relevant to the measurement task are checked. For example, before a field strength measurement, the functionality of the equipment used to detect and display the measurement values may be checked with respect known reference signals or emissions. The functional test documentation may be part of the measurement report.

2.3.4.3.2.2 Built in test (BIT)

BIT that is based on monitoring system resources (e.g. calibrated signal generators) will verify the proper operation of the station and will be a central element in assuring the station operability.

The BIT activation may include three methods:

– automatic BIT performance upon Power ON;

– automatic periodic operation – every several hours, 24 h for example;

– operator initiated (including possibility of remote execution initiation).

BIT results should be available to local operators and remote staff in the control station.

Sometimes multiple elements of the spectrum monitoring station can provide individual self-test functionalities, for example, within a multi-receiver monitoring system. In these cases, the integrated test of all system components is sometimes referred as BIST, Build in System Test.

2.3.4.3.2.3 Enhanced functional tests

The enhanced functional test is performed at fixed intervals, e.g. monthly or quarterly, by the measurement staff or may be automated.

In contrast to the basic test, the enhanced functional test covers the entire operational range of the measuring equipment or system and is not only related to a specific measurement task.

Several items of the same type (or similar type) of measuring equipment should be grouped to form a system and tested collectively. By doing this, enhanced functional tests can cover all the equipment at a test site or in a monitoring vehicle.

The checks are to be documented in a test report that contains details of the nominal value, permissible tolerance and measured (actual) value for each parameter to be tested.

2.3.4.3.3 Scheduled maintenance

Normally, a technical department supporting the monitoring service takes care for the maintenance of the measuring equipment. These activities are usually carried out in a dedicated workshop and not at the test site or in the vehicle.

The maintenance work differs from the functional tests in that it is considerably more thorough and comprehensive. The content of the maintenance schedules generally corresponds to the manufacturer's measuring equipment specifications.

A maintenance schedule is required for each measuring equipment or system, setting out the technical parameters to be checked, together with their nominal values and tolerances, as well as the maintenance instructions and intervals. The maintenance work performed is documented in a relevant report.

The scheduled maintenance activities consist of more extensive (relative to the BIT) manually administered tests, that may use external test equipment and care for mechanical elements such as lubrication of moving parts, cleaning, protection from dust and moisture, and protection from corrosion and erosion.

The scheduled maintenance activities are usually done according to the relevant manufacturer instructions, by the manufacturer itself, or by authorized local support agents under a comprehensive maintenance and support agreement.

2.3.4.3.4 Calibration

To maintain accurate performance of antennas and measuring equipment according to their specifications, calibration of the equipment at regular intervals is recommended. Calibrated equipment guarantees that measurement results are within the specified measurement uncertainty of the actual value.

Measurement uncertainty can be defined as that part of the expression of the measurement result that states the range of values within which the true value is estimated to lie with a defined probability (confidence level). For example, the result of a field strength measurement might be expressed as 30 dB(μV/m) ± 2.5 dB (with 95% confidence), which means that one can be 95% confident that the true value of the field strength lies between 27.5 and 32.5 dB(μV/m).

In contrast to the functional tests and maintenance, calibration traces the technical parameters such as frequency and signal level, to the defined absolute accuracy of a national or international standard through an unbroken chain of comparisons.

Primary reference standards may only be used for calibration and are maintained by national calibration authorities or their subordinate organizations. Where this is not possible to use a primary standard, the calibration laboratory tasked should define procedures for achieving traceability the primary standards through a chain of transfer or working standards.

Traceability works because there is a fixed relation between every standard within the calibration hierarchy and the national standard. Each working standard is regularly compared with the reference standard of the same level, and the latter is in turn compared with a reference standard of the next higher level. This leads to an uninterrupted calibration chain.

Monitoring stations use a relatively large number of specialized equipment to perform the various measurement tasks. The parameters most frequently measured include frequency and field strength, using antennas, monitoring receivers, and spectrum analysers. Hence the focus should be on the calibration of the frequency reference, signal level and antenna gain as these values may be of legal significance when evaluating the compliance of emitters to the authorized parameters. However, there are also evaluations that can be performed with uncalibrated equipment, such as emitter location. It is therefore necessary to determine which equipment absolutely must be calibrated to reduce operational costs associated with the calibration procedures.

In some cases, the calibration costs may be too high to be regularly applied, for example, for large antenna systems. In such cases, it is of particular importance to record reference values when putting the measuring equipment into operation since the measurement uncertainty is at its lowest at that point in time and can serve as a reference for later functional tests and maintenance work.

It is not possible to calibrate DF systems in a laboratory. However, to maintain the accuracy of the DF, bearings of known transmitters in various frequency bands should be taken and recorded. The accuracy of the DF can be regularly measured as described in Recommendations ITU-R SM.2097, ITU-R SM.2060 and in Report ITU-R SM.2354, and the performance evaluation of mobile direction finders can be measured as described in Recommendation ITU-R SM.2140. Substantial deviations from prior results are an indication of possible defects.

In the case of measurement systems, it is often only possible to calibrate individual components such as the receiver(s). Errors from other components in a measurement system, such as feedlines, attenuators, switches, couplers and antennas, should also be considered when assessing the measurement uncertainty.

Each calibration is to be documented in a detailed calibration report to accompany each item of equipment. The calibration report contains full documentation of the measurements made, including the values measured. Each item of equipment should therefore be reliably and permanently marked or labelled, etc. to indicate its

calibration status. The calibration reports are incorporated in the equipment file when the equipment is put back into service.

At the time of the development of this Handbook, there was undergoing work by the international metrology community to establish machine readable formats for calibration certificates. These are known as "Digital Calibration Certificates", commonly referred by its abbreviation "DCC". It is expected that the adoption of such format will enable better use and management of the calibration data, including automated workflows for error correction and uncertainty evaluation.

It is not possible to specify a standard calibration interval. Intervals of one year are common. There is, however, no generally applicable period. The calibration interval should be chosen from a technical viewpoint by assessing the varying measuring equipment characteristics and considering manufacturer recommendations.

Calibration places high demands on the technical equipment used. This equipment cannot generally be provided by a monitoring station's normal workshop. The expense of installing and maintaining a calibration laboratory within the authority can be justified only in large organizations, since only they have larger numbers of equipment that enable full utilisation of the calibration laboratory's capacity.

In many cases it makes more economic sense to outsource calibration of the equipment to either the manufacturer or an external calibration laboratory. This eliminates the need to set aside resources for premises, equipment and trained staff.

Some manufacturers of spectrum monitoring equipment who market and sell their products worldwide also operate regional service and support centres at various locations around the globe. These centres are equipped with, amongst other things, portable calibration sets and standards. A calibration team is paid to check and calibrate the radio monitoring equipment at regular intervals. Calibration issues related to specific systems (such as radio direction-finders) are discussed in more detail in other sections of the Handbook covering those systems.

2.3.4.3.5 Repair

Measuring equipment outages owing to technical defects or deviation from the permissible tolerances cannot be prevented. To ensure a smooth measurement operation, a repair service should be engaged to react quickly to equipment failures and provide replacements.

Technical staff responsible for installing and maintaining equipment forms a vital part of every monitoring service. Constructing minor electronic or mechanical devices and locating faults is also part of their job. Setting up an internal workshop guarantees short routes and rapid response times and largely reduces the need for spare parts to be kept.

However, it is often not worth smaller monitoring stations having their own workshop with comprehensive repair facilities. In this case, a central workshop serving several monitoring stations or maintenance service contracts with manufacturers or authorized specialists are better and more economic alternatives.

When a centralized or external repair service is used, the administration may purchase spare parts or additional monitoring equipment units to ensure smooth operations.

NOTE – In addition to repairs, suppliers of the equipment may also offer to maintain it.

2.3.4.3.6 Spare parts

The number of spare parts to be purchased may be defined considering the manufacturer's recommendations and provided historical statistics of equipment failures. It will thus vary for each equipment model and usage conditions.

In practice it is extremely hard to define the number of spare parts needed for any system and it's more likely that any initial estimate will be partially wrong, resulting in some spare parts not being used during the entire equipment life cycle, and other parts being more required than originally expected.

It may not be advisable to maintain a large amount of spare parts because electronic equipment degrade regardless of their use, i.e. may also have a shelf-life and require ongoing maintenance to assure availability.

Finally, fast development cycles of modern spectrum monitoring equipment may result in early obsolescence of purchased equipment, rendering fruitless any pre-emptive efforts to maintain stock of spare parts.

Administrations may also consider other alternatives to purchasing directly spare parts, such as maintaining a support contract for a longer period, e.g. five or ten years, and includes the provisioning of any required parts and a service level agreement to ensure equipment availability and reduced mean time to repair.

Other alternative is to simply rely on recurrent purchases of new equipment and maintain a slightly larger number of stations and equipment in operation, such as that any individual failure that may result in equipment unavailability for a longer time, e.g. 8 to 12 months, do not strongly affect normal operations.

2.3.4.3.7 Software maintenance

Software components used in spectrum monitoring systems also require modification, repair, and updates to keep functionality due to changes in the underlying processing infrastructure, operational systems and other ancillary components.

Furthermore, the constant evolution of cyber security threats may require patches and updates to correct vulnerabilities that pose risk not only to the monitoring system itself, but also to other systems within and outside the administration network.

Such updates require professional support, hence it is recommended to subscribe to a software maintenance service from the supplier of the system.

Software maintenance not only include those tasks related to changes in the software itself but also require regular activities such as user management and access control, system and network configuration, data and application backup.

Some of these tasks may be supported by the administration IT (Information Technology) personnel due integrations that may be required between the administration's corporative network and the spectrum monitoring network. Other alternatives are also possible and practiced by administrations, including the use of separate network infrastructure maintained either by authorized local support agent of the supplier of the system or by the some of the spectrum monitoring personnel.

2.3.4.3.8 Management of the system maintenance information

It is recommended to keep track of maintenance activities by logging all relevant information.

The maintenance log may include:

– Status of the spare parts (ready in stock or faulty in a repair process).

– Follow up and register of scheduled maintenance activities.

– Failure detection reports and follow up of the corrective actions (for hardware and for software).

– For each equipment item the Administration will keep a history file with relevant maintenance activity and repairs. The data in this file will enable statistical analysis of the equipment operation and reliability.

As a rough estimation, the scope of the overall yearly maintenance (spare parts, repairs, schedule maintenance) and support of a monitoring system is on the order of 10% of the initial cost of acquisition and setup of system.

2.4 Support management system

To support decision-making at a managerial level, administrations may employ support systems to manage information related to spectrum monitoring requests, resources and activities.

The management process can be considered either as a feedback structure or as a combined top-down and bottom-up process. A management information system, consisting of a database and associated reporting system, will provide relevant and timely information to develop resource plans in support of new monitoring tasks.

A resource plan will define the locations, schedule, personnel (skill and experience), and equipment capabilities needed to address a specific monitoring task. Depending on available information and resources, it may be appropriate to set up a resource plan first and use it as a basis for the working plan.

2.4.1 Database

To gain an overview of the monitoring tasks, the time required for dealing with them, and their regional distribution, the following information is needed from the monitoring database:

– unique task number;
– code for the type of task (e.g. interference report, occupancy measurements);
– date of receipt and completion of task;
– entity requesting task or source of interference report with address, telephone, fax number and e-mail address;
– identification of the location of the interference or measurement by name and numerical code, such as postcode or coordinates;
– task description or content of the interference report;
– affected service or application;
– frequency or frequencies;
– call sign;
– frequency license numbers, if individually assigned;
– category of the station (such as fixed, mobile);
– in interference cases, cause and source of the interference.

It may be useful to input further data such as manufacturer, type and serial number of the interfering or interfered-with device, any foreign countries or military locations affected, steps taken (e.g. fines imposed), recipient of the final report, names of personnel involved in the measurements, etc.

Uniform and unambiguous analysis of the data can be aided by using a hierarchically structured menu for inputting the type of task, service involved, source and cause of interference, as illustrated in the example below.

Layer 1	Layer 2	Layer 3	Layer 4
1 Occupancy report	1-1 Terrestrial services	1-1-1 Fixed service 1-1-2 Mobile services	... 1-1-2-1 Land mobile service 1-1-2-2 Aeronautical mobile service 1-1-2-3 ...
		1-1-3 Broadcasting service	...
2 Interference report	1-2 Space services	1-1-4 …	

The hours worked, divided into office and field work, and vehicle mileage can be recorded for each individual task. It may also be necessary to note the equipment used to support some forms of analysis.

As the data referred to in this section supports analysis of management information, measurement data such as field strengths, occupancy rates and other results are not used. Nevertheless, the data mentioned in § 2.3.3 can be stored in the same database (monitoring database), thus allowing both individual cases to be analysed and statistical analyses to be carried out.

2.4.2 Reporting system, statistical analyses

Once the data has been stored into a database, various types of analysis are possible. For planning purposes, it is important to have an idea of the time needed for the various tasks. Graphs covering several years clearly indicate typical trends. For example, should working hours invested in occupancy measurements decline

(because management demand for such values has decreased or because remotely controlled equipment is being used to a greater extent), manpower will be available for other tasks.

Unless such information is supplied to management well ahead of time, there is a risk of incorrect decision-making as management may not be familiar with the details of monitoring procedures and techniques. Increasingly, Administrations require exact data about the total number of tasks completed and the resources used which drive costs. These costs will drive the budget process and influence the fees payable by various frequency user groups, and, should the need arise, as evidence in court to justify legal compensations.

The format of standard reports and statistics should be specified to ensure uniform data compilation and data comparability. However, this does not imply that the information should be distributed to all recipients in the same format. The information requirements of the head of a monitoring station are usually quite different from those of his superior (head of the Administration). The data therefore needs to be tailored to individual recipient's needs.

Analysis of statistical data often leads to further questions. Therefore, it should be possible to customize database queries for special reports without the need for additional programming.

For example, when identifying the most interfered-with service, the question automatically arises as to the primary source of the interference, which then leads to the question regarding the mechanism actually causing it. The answers to these questions may well be of importance in the context of radio equipment inspections, standardisation and market surveillance. Above all, they will indicate whether remedial measures should be taken in relation to interfered-with or interfering equipment.

When designing a reporting system, hypertext mark-up language (HTML) techniques should be considered. The key feature of HTML is its capability of handling different types of data such as text, pictures and graphs and presenting them in a unified layout by using a simple browser.

2.4.3 Working plan

When developing a working plan, a distinction is to be drawn between tasks which can and cannot be planned. While it is usually possible to predict the number of routine frequency occupancy measurements and the associated time required for completion, it is not possible to accurately predict the number of incoming interference reports and the time required for mitigation.

Planning is typically based on the schedule of special events, changes in the radio services, and the previous year's working plan, taking account of any noticeable increase and/or decrease in tasks. Early consultation with the entities requesting monitoring tasks is necessary to accommodate changes to the plan. Modifications to the regulatory framework affecting telecommunications also may need to be taken into consideration.

To support development of the working plan, records of all individual tasks should be available in the database to enable a statistical analysis of the volume of and time required for the tasks. The working plan should also account for unpredictable requirements and may need to be revised in the course of the year.

2.4.4 Resource planning

The working plan forms the basis for resource planning which constitutes another complex task involving several functional inter-relationships. A comparison with the previous year's working plan will indicate any increase or decrease in the demand for personnel, training, vehicles, and measurement equipment.

The automation of measurements in newer models and the integration of several functions in a single device may lead to a decrease in the number of staff required and to smaller vehicles. However, such developments may require additional training to improve the qualifications and readiness of the operators and maintenance staff.

The matter is further complicated by the fact that changes in telecommunications and technical measurement requirements emerge at such short notice that they cannot always be considered adequately in medium-term budgetary planning (three to five years).

From experience, the following advice seems relevant: when replacing equipment, special attention should be paid to equipment for which spare parts are no longer available. Equipment taken out of service should be physically removed from the monitoring station to avoid additional costs from inadvertent maintenance and storage of the obsolete equipment.

2.5 Siting, buildings, facilities

2.5.1 Siting of monitoring stations

2.5.1.1 General considerations

This section provides general guidelines for monitoring station site selection and identifies some of the pitfalls to be avoided. Some fundamental decisions have to be communicated to the planning group in advance of the actual selection of a site, so that the station may adequately serve its intended purpose. These include:

– the frequency ranges and geographical areas to be covered (see also § 2.2.2);

– whether domestic monitoring or monitoring of signals from outside national borders is more important;

– requirements for special installations such as long-range direction finders, field-strength recording facilities, or directional antennas;

– acceptable on-site field strengths from nearby transmitters in the frequency ranges of concern (see Recommendation ITU-R SM.575);

– administrative considerations such as availability of housing, shopping facilities, schools for dependants, local transport and utilities;

– land costs.

The importance of administrative considerations should not be minimised. Experience has shown that it is difficult to retain qualified technical personnel at civilian monitoring facilities if normally expected amenities are not within reach. Demographic changes and physical growth projections of an area under consideration for a monitoring station should also be considered for siting decisions to prevent undue encroachment.

2.5.1.2 Desirable minimum site criteria for a station

Sites for spectrum monitoring stations should have suitable RF conditions and comply with three major principles. They should be:

– located in places suited to the zone to be monitored (suitable geographical coverage);

– protected against obstacles that may distort or block signals or services to monitored;

– electromagnetically protected from nearby strong transmitters.

As far as possible, a site should be selected where the field strengths of the emissions to be monitored will be relatively undisturbed by the local structures or terrain features. Particularly, sites used for measurements below about 30 MHz should consist of level terrain situated in a relatively level area with relatively high conductivity and free of gravel or outcroppings of rock. Nearby overhead conductors, buildings, large trees, hills, and other man-made and natural features may seriously distort or disturb the wave front of the emission. The degree to which these conditions limit the validity of the measurements depends on several factors including the frequency range, type, and orientation of the monitoring antenna. At VHF and UHF frequencies, where highly directional antennas are used, it is important that the path in the general direction of the signal source be unobstructed; additionally multiple-path reception due to local reflection or re-radiation of the wanted signal should be minimized.

If the site itself does not comply with the above-mentioned principles at ground level for VHF/UHF, the situation may be improved by providing sufficient clearance of the antenna towers with respect to nearby obstacles. It may not always be possible to group multiple monitoring antennas on one tower as this may lead to unwanted coupling and distortion of the antenna patterns resulting in measurement errors. Antenna masts can be lattice towers or be made of concrete. Depending on the local conditions, the erection of a lattice tower may be less expensive but the recurring maintenance costs should also be taken into account. A tower should withstand the weather conditions in the area, e.g., wind- and ice-loading. The antenna tower should allow easy and secure access to the antennas, to amplifying, filtering, and switching equipment installed near the antennas, and to the lightning rod on top of the tower.

For satellite monitoring facilities, several aspects should be considered when choosing the site, depending on the target of monitoring (GSO, non-GSO satellites or both). For GSO monitoring stations, the visible geostationary arc should be as wide as possible and include the orbital position of the satellites of interest. Monitoring of non-GSO satellite emissions requires good horizon visibility so that the time satellites can be observed from the monitoring station can be maximized and it is possible to track satellites effectively. Elevated terrains may be considered to have a better orbital arc visibility while flat grounds surrounded by far enough away mountains can offer excellent protection from terrestrial interference, which is common in open areas.

In addition, space monitoring stations require larger spaces to set-up different antennas for the different bands of interest to monitor and track, also considering the difference between the uplink and the downlink frequency bands and the use of full motion parabolic antennas. Depending on the frequency band, the parabolic reflector diameters can reach large dimensions, up to more than 10 meters. Antennas should be properly distanced to preserve clear line of sight, as detailed in § 6.1.6. For detailed characteristics of the space signals monitoring facilities operated by several administrations see the Annexes to Report ITU-R SM.2182.

The site should be physically separated from existing (or potential) industrial or congested residential districts. At least 1 km separation distance is desirable, and even greater spacing may be required from certain types of industrial plants utilising electrical welders, high power industrial heating devices, diathermy equipment, smoke precipitators, and other machines with significant levels of radio-frequency energy. With respect to protection from strong fields from radio transmitters, see § 2.5.1.4.

High-tension power transmission lines may be a source of wide-band noise interference if they are near either the monitoring building or the antennas. A minimum of 2 km clearance from lines exceeding 100 kV is desirable and much greater clearance (up to 10 km) may be required for extremely high-voltage lines or where extensive monitoring of very weak signals is planned.

Proximity of airports or heliports is important to consider when siting a monitoring station, especially at the higher frequencies, because low-flying aircrafts reflect sufficient energy to cause out-of-phase, multipath reception of signals being monitored. Experience has shown that monitoring stations should be sited more than 8 km distant in the direction of the runway approaches, or 3 to 4 km in other directions. Greater distances would be preferable when considering the operations of space monitoring stations to protect the reception of low power flux-density at the Earth receiving antenna.

Monitoring stations (including antennas) should be sited sufficiently distant from roads with heavy traffic to minimise ignition interference (e.g. 1 km). The site should be accessible by an all-weather road and adequate utilities such as commercial electric power, telephone service and water should be available or obtainable. If the monitoring station includes a direction finder, then the highest priority consideration should be given to the direction-finder site criteria given in § 2.5.1.3. Direction-finder site criteria cannot be compromised if accurate bearings are required.

Monitoring stations should be sited sufficiently far away from recharge stations for WPT-EV (existing and planned), in particular for frequencies below 30 MHz. More information on WPT-EV characteristics and emission levels can be found in Report ITU-R SM.2451.

Station planning should also consider potential developments in the surrounding area. This is particularly crucial for space monitoring stations, for example, given the high cost of installation of such facilities. Such stations should operate effectively for a long time. Therefore, it is important to study and understand how the surrounding landscape could be modified, due to the expansion of nearby urban areas or the building of new roads or infrastructures which might have an impact on the operations of the station. Knowledge of the local regulations regarding development of nearby infrastructures or urban areas is therefore essential.

2.5.1.3 Additional criteria for siting stations equipped with direction finders (DF)

If a DF is to be installed, it is also desirable that no mountains, hills, large man-made structures, or other obstructions project to a vertical angle of more than 3 degrees above the horizon as viewed from the proposed site or the DF antenna. There should be no valleys or other major depressions within 1 000 m of the site of the DF, and even greater spacing to natural terrain features is desirable.

Maximum terrain deviation from the reference ground elevation at the centre of the DF should not exceed about 1 m within a 200 m distance to avoid expensive ground preparation costs when constructing the DF.

When completed, the land within several hundred metres of the DF should be essentially flat (or slightly crowned to facilitate water drainage).

The selected site for the DF should avoid locally concentrated areas of wet or exceedingly high conducting soil. Also, discontinuities in the substrata should be avoided, particularly when obvious surface features imply them.

Large, buried conduits or metal pipes (such as petroleum transmission lines) may, unless deeply buried, cause direction-finding measurement errors if they are in the immediate area of the DF. A minimum separation of 200 m is recommended.

Any single half-wave (λ/2) structure, resonant at any frequency within the operating frequency range of the DF should be separated by at least 15 wavelengths. Any single quarter wave (λ/4) structure, resonant at any frequency within the operating frequency range of the DF and positioned in the same polarization plane should be separated by at least 7 wavelengths. For example, at an operating frequency of 25 MHz (where λ = 12 m), a conducting object with a length of 6 m (λ/2) should be at least 180 m distant from the DF.

NOTE 1 – When more than one of the quarter wave or half wave structures referred to above are noted at any reasonable distance from the DF, a special study on the impact of DF performance may be required.

Wind turbine operation in the vicinity of a DF may deteriorate the performance. Scattering from the blades consists of a slow low amplitude variation at the geometric rotation repetition frequency (one-third the rotation rate) of the blades, as well as a large amplitude but short duration (about 30 ms) interference. In the forward scatter region, the receiver antenna pointing towards the monitored transmitter also points towards the wind farm, and the antenna directivity is of little benefit in reducing interference effects. The height of the monitoring antenna can be critical, as ground reflections can result in significant signal reduction (see Report ITU-R BT.2142 – The effect of the scattering of digital television signals from a wind turbine, p. 47), and Report ITU-R SM.2391 – The effects of wind turbines on fixed radio direction finders.

A careful consideration of wind farm plans should be taken when choosing the right site for a monitoring station that includes DF equipment.

Below 30 MHz, the additional "man-made" noise from wind turbines may also impair the sensitivity. If the wind turbines obstruct the line of sight between the monitoring antenna and the transmitted signal, the measurement accuracy may be degraded.

a) Direction finders below 30 MHz

The requirements listed below and in Table 2-1 are of particular importance when choosing a site for DF stations operating below 30 MHz. In general, the site should have a soil of uniformly high conductivity, a flat surface, sufficient distance from all metal obstacles, in particular high-tension power lines, sufficient distance from all metal piping or conduits (even when buried), sufficient distance from railway lines, public highways, built-up industrial or commercial areas, trees, buildings.

In general, reception will be better on open flat grounds where the water table is near the surface than locations surrounded by hills or mountains. In case of hilly terrains, a possible choice could be a plateau, with the highest possible soil conductivity, overlooking the surrounding hills.

TABLE 2-1

Minimum distances between obstacles and direction finder

Obstacle	**Minimum distance (m)**
Isolated trees	100
Non-metallic one-storey building: – a single building – a group of buildings	 100 (in HF depending on the size and the shape of the antenna more than 100) 200
Small groups of trees	200
Metal fences	200 (in HF depending on the size and the shape of the antenna more than 200)
Small antennas	200
Two- or three-storey non-metallic buildings	250
Small buildings with metal roofs	250
Open-wire telephone lines, low-tensions lines	250-300
Non-metallic buildings of over three storeys	300 and over depending on height
Large antennas	400
Metal structures (small sheds, etc.)	800
Forests	800
Lakes, ponds, rivers	1 000
High-tension lines with pylons 20 m high	1 000
Railway or tram lines	1 000
Reservoirs, large metal structures, metal bridges	1 500
Wind turbines	2 000 from individual wind turbines 5 000 from wind farms
High-tension lines with pylons of 30 m and over	2 000-10 000

As far as possible, the following rules should be used as a guide:

– the terrain should be chosen to avoid gradients of more than 1% within a radius of 100 m for HF installations and 250 m for MF and LF installations;

– outside this zone, the slopes can become steeper as the ground drops away, but excessive or sudden changes in ground level should be avoided;

– the angle between the horizontal and a line joining the direction-finding antenna and the top of any obstacle should not exceed 2° or 3°;

– the ground should be completely clear within a radius of at least 200 m of the antenna;

– all incoming cables connected to the direction-finding antenna should be 1 or 2 m underground within a distance of 30 m from the centre of the antennas. This depth can be reduced to about 0.5 m between 30 m and 250 m.

DF antennas should be located as far as possible from other monitoring antennas as the receiving antennas of the monitoring station obstruct the regular propagation of radio waves, thus introducing errors into the bearings obtained.

If an Adcock system is used, the cables in the first section should lie along the line formed by an antenna pair or, if this is not possible, they should be laid at an angle of 45 degrees with respect to each pair.

Table 2-1 gives comprehensive information on the minimum distances required between obstacles and the centre of the antennas, to minimize the impact on the accuracy of DF measurements.

b) Direction finders above 30 MHz

For VHF/UHF DFs, the minimum distances of Table 2-1 may be reduced.

Since VHF/UHF monitoring stations often require to be installed in (or close to) congested urban areas, e.g. on buildings or roof tops, the definition of RF protection zones may be appropriate. An RF protection zone is one in which there are a limited number of RF emitters active within a distance from the monitoring site. Two different types of zones should be considered.

In the first, smaller zone, the use of fixed and mobile radios may be restricted. For practical reasons it will be difficult to enforce such a rule outside the station's area. In a larger zone, the use of high-power ISM equipment and major obstacles such as multi-storey buildings and industrial plants may be restricted. The legal prerequisites for the creation of such restrictions are completely different from country to country.

2.5.1.4 Protection from strong transmitter fields

Monitoring sites should be free from the influence of strong emissions and other sources of interference because, dependent upon the frequency ranges to be covered, the presence of nearby radio transmitters may severely limit the monitoring capabilities due to intermodulation and blocking effects.

In evaluating the possible adverse effects of such transmitters, the field strength of both the fundamental signal and the harmonics should be considered. The presence of two or more strong transmitters should also be considered, even if their operating frequencies are vastly different from the frequencies of the monitoring station because intermodulation products may fall into the frequency range of the monitoring station.

Recommendation ITU-R SM.575 describes a general method to calculate the maximum permissible field strength at a monitoring receiver based on the following input parameters:

– immunity of the receiver against strong signals (3rd order intermodulation products level);

– sensitivity of the receiver;

– external noise level;

– antenna gain;

– attenuation of the RF cable between the antenna and the receiver;

– bandwidth and frequency of the disturbing signal(s).

As the reference bandwidth is frequency dependent, the resulting maximum field strength is frequency dependent.

Moreover, such parameters may vary within a wide range. The resulting field strength value then depends on the selection of reasonable and typical values of the above parameters.

Calculations of the maximum field strengths in Recommendation ITU-R SM.575 assumes matched dipoles as monitoring antennas and the use of the maximum sensitivity of the receiving equipment, i.e. with 0 dB RF attenuation. These values may apply for active omnidirectional antennas and direction finders, in which cases intermodulation products on certain frequencies are expected to be visible above the noise floor, if the maximum field strengths are exceeded.

However, if passive directional monitoring antennas are used, allowable field strengths may be higher or lower, depending on the direction in which the antenna is pointed. Especially when the strongest field strengths come from one site, performance of the monitoring system may only be affected in this direction, but not in others. Furthermore, band reject filters can be applied to attenuate the frequency (ranges) producing the highest field strengths in which case the monitoring system becomes fully usable even if the values from Recommendation ITU-R SM.575 are well exceeded.

If it is unavoidable that a monitoring station is to be installed at a location with higher field strengths than the maximum values from Recommendation ITU-R SM.575, it should be considered to limit it to rotatable directional antennas instead of a direction finder.

2.5.1.5 Protection from local computer systems

It has been found in many cases that various components of computer systems may emit electromagnetic radiation and cause interference to the monitoring and measuring equipment. Although special low-interference computer equipment for radio monitoring systems has become available, most of the computers in use are standard PCs.

After the installation of a computer system, it is very difficult to detect the source of interference since the computer equipment and its peripheral components are normally distributed throughout several rooms or even the whole monitoring building. The interfering signals may be emitted by the components and/or conducted via the computer cables. Furthermore, interfering signals may often occur both on the fundamental (clock) frequencies and on the harmonic frequencies. The most appropriate way to detect the interfering source is to subsequently shut down and disconnect the various computer components.

In any case, the monitoring service should observe the following recommendations:

– Only double shielded coaxial cables should be used for connections between the antennas and the receiving equipment.

– Shielded cables should also be used to connect the individual components of the computer system.

– Where possible, general purpose computer components should not be installed near receiving and measuring equipment.

– In the case of interference, any computer equipment which is not needed should be disconnected or powered down.

– In general, monitoring offices should be situated close to the antennas and be separated from administrative offices.

– Measures to avoid or minimise interference caused by computer equipment should be incorporated into the planning phase of the monitoring station. It is recommended to seek advice from monitoring services with experience in this field.

2.5.1.6 Land requirements

The amount of land required for a monitoring station and the layout of its facilities depend largely on the mission and activities assigned to the station and whether it is manned or not. A station used for HF monitoring requires much more space for the antennas of the DF system than a station for VHF/UHF direction finding or if local monitoring is the most essential task. Stations engaged in signal field-strength recording will require additional land to provide adequate clearance from overhead conductors and other obstructions for the antennas.

Property adjacent to a monitoring site is also an important factor. For instance, where a monitoring station is to be situated in a rural area, there may be less likelihood of interference to operations than in a congested area where factories or commercial sources of interference exist (or being contemplated). To prevent the degradation of a monitoring site due to nearby construction, additional land can be acquired to provide the necessary separation distances from potential obstructions and sources of interference.

Provided that adequate protection from potential noise sources is ensured by agricultural or unused land around, an area of 40 000 to 160 000 m^2 is sufficient for a manned monitoring station equipped with a VHF/UHF direction finder and with limited requirements for MF or HF directional antennas. A separate area of another up to 90 000 m^2 is needed for the installation of an HF direction finder, depending on its design. Taking into account the figures of minimum distances in Table 2-1 it becomes obvious that areas of 400 000 m^2 or even more are needed if adequate protection cannot be otherwise guaranteed and all equipment and facilities should be situated on a coherent plot of land. For monitoring stations with an exceptional need for a large, long-range DF used at frequencies below HF, a limited number of large directional monitoring antennas, and with radiocommunication facilities, an area of 320 000 m^2 to 640 000 m^2 may be needed, depending on antenna designs. In some exceptional cases where monitoring stations have several large directional monitoring antennas, isolated field-strength recording facilities, and separate radio-net control or relay duties, an area of up to as much as 1 200 000 m^2 may be needed.

The area needed for the installation of a remote-controlled VHF/UHF monitoring station is primarily determined by the size of the antenna tower. An area of 30 m^2 may be sufficient for the antenna tower and an equipment shack. If the antenna mast has a height of, e.g., 80 m, more than 100 or 200 m^2 may be required.

Also, legal aspects related to operational safety and public safety may need to be considered. Icicled antenna elements for example can pose an injury threat and require fencing at some distance from the mast, which of course increases the requirement for land.

2.5.1.7 Roadways

In addition to access roads from public streets to the monitoring stations and its buildings, service roads should normally be provided to all DFs, antennas, field-strength recorder booths and other outlying facilities so that motor vehicles may be used to convey equipment to and from these sites. These should be all-weather roads suitable for the terrain and soil conditions to ensure operation throughout the year.

2.5.1.8 Fencing

Fences may be desirable to protect the plant from livestock or wild animals and, in some cases, from human intruders. Depending upon the local circumstances, the entire property may be fenced, or it may be determined that only the building area requires fences.

If a decision is reached to install metallic fences, they should be sufficiently remote from critical installations, such as long-range DFs and field-strength measurement installations (usually 200 m or more) to avoid possible interference to the proper operation of such devices.

Metallic fences should be well grounded to ensure that there are no floating conductors that can resonate and re-radiate stray electromagnetic energy.

2.5.2 Buildings and auxiliary facilities

2.5.2.1 Buildings

2.5.2.1.1 Monitoring buildings for manned monitoring sites

Depending on the separation from the monitoring antennas or direction finder, it is recommended that the building should have no more than three storeys above ground level. If a multi-storey building or a single storey building with a basement is selected and if a large quantity of equipment is contemplated at the monitoring station, the design should take account of the concentrated weight of the monitoring racks and equipment and the need for an adequate capacity for the floor loading in those areas.

In the case of unmanned stations provisions for the protection of the building and the equipment from vandalism should be made, e.g. by using concrete buildings with trellised windows. Remote monitoring units for the detection of intrusions, power breakdown and fire alarm should also be considered.

In the case of manned monitoring stations there are basically two different concepts possible. Some administrations concentrate their monitoring operations in a single room; others have found it expedient to separate certain functions from the main monitoring room. For example, if there is sufficient staff and if there will be extensive associated communication activities; it may be desirable to install the communication terminal equipment and operating position in an adjoining room. On the other hand, where there are limited staffs, the communications operations will normally be performed by the monitoring personnel as a collateral duty, so that the communication facilities should be readily accessible from the monitoring position. Similarly, if there is extensive special work (e.g. long-term propagation studies) to be performed in addition to the normal monitoring and measurement duties, it may be desirable to perform such operations in a separate room.

2.5.2.1.2 Allocation of space

Not only the amount of land required but also the space requirements of the monitoring building very much depend on the mission of the station. National legislation related to occupational health, other safety aspects and ergonomics may largely expand the minimum space requirements as the following example indicates. From the technical point of view equipment should have sufficient distance from the wall so that maintenance

teams are able to replace the equipment. From the job safety point of view additional space may have to be allocated enabling staff to pass by even when all cabinet doors are open. Two different examples A and B are presented below and may be considered as possible starting points for planning. It should be stressed that these examples are for reference and will need to be adapted to individual administration needs. Moreover, with a trend of decreasing monitoring equipment size, space requirements can be reduced.

Example A

This example represents a monitoring building for a staff of twenty or less which includes space for combined supervisory, monitoring and office personnel. The building consists of a main monitoring room with two small special project rooms adjoining. Offices are provided for a supervisor and also for administrative/clerical personnel. Additional space is provided for an electronic repair shop, kitchen, meeting room and utility, sanitary and storage facilities. An outline drawing of such a building is found in Fig. 2-3, showing how such space can be allocated. Example dimensions are found in Table 2-2.

Example B

The building which is presented in example B could be used where more space is needed for a larger staff or multiple monitoring positions. The area dimensions given in Table 2-2 may give an impression of the size of such a building, which could support a larger monitoring staff with more functions. Such a building could accommodate about 35 to 40 persons of the radio monitoring service as well as additional staff for the radio inspection service and other sections. It should be mentioned that typically a fraction of the 35 to 40 persons mentioned work in the building at the same time (others are mobile, off shift, on holiday, etc.).

FIGURE 2-3

Example of a floor plan for a monitoring station building showing how workspaces could be allocated (not all building details are shown)

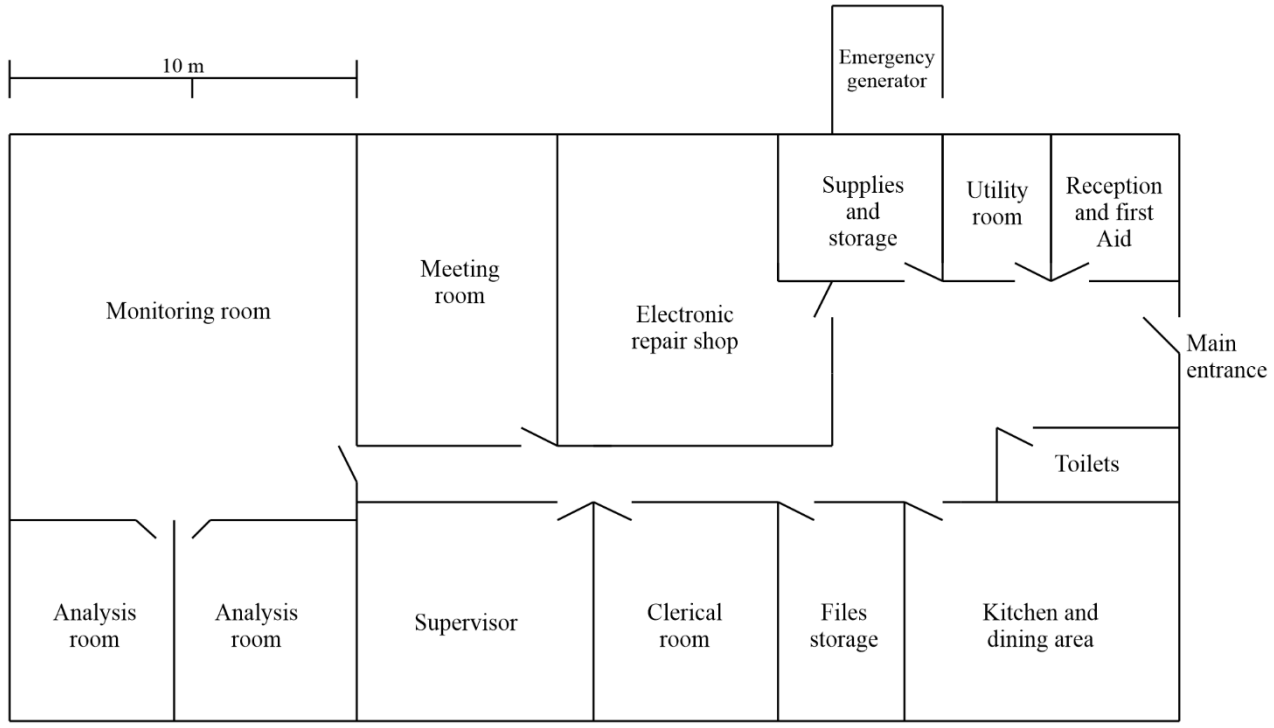


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TABLE 2-2

Example of space allocation for monitoring station buildings

Purpose	Example A approximate area (m^2)	Example B approximate area (m^2)	Remarks
Main monitoring room	100	190	
Electronic repair shop	50	60	
Mechanical repair shop (if separate)	–	25	
Meeting room	50	50	Small meeting space may alternately be in supervisor office
Office accommodation	15-40	15-40	In some cases offices (e.g. administrative) may be occupied by more than one person
Copy machine and file storage	(part of clerical office)	24	In some cases additional rooms for file storage could be located in the basement
Server and telecommunication equipment	10	31	Utility room or basement
WC	10-15	25	May be multiple rooms and room sizes and facilities may be dictated by local building codes
Dressing room	–	6	
Kitchen	50 (including dining area)	6 (kitchen only)	Dining area may be part of kitchen or shared with meeting space
Cleaning equipment	–	6	
Equipment and antenna storage	10 (may be more space in outbuildings)	100	May be partly be in basement or outbuildings
Caretakers storage	–	30	
Heating	5-10	36	Basement or utility room
Emergency power plant	(outbuilding or external)	36	Basement
Uninterruptible power system	10	10	Basement
Power transformer	(external)	10	Basement
Garage (if monitoring vehicles at site)	100	300	

2.5.2.1.3 Acoustic treatment

Acoustic tiles or other acoustic treatment of the ceiling (and perhaps the walls also) should be provided in the main monitoring room and special project rooms. Acoustic treatment of some other rooms may, in some instances, also be desirable.

2.5.2.1.4 Shielded rooms

If extensive use is to be made, either in the special purpose rooms or in the electronic repair shop, of high-output signal generators or other sources of radio-frequency energy which might cause interference to monitoring operations, consideration might be given to shielding such space by means of appropriate

continuous screening in the walls, ceiling and floor. Shielding is not normally required if the signal generating equipment is typical of that used for normal equipment maintenance and testing procedures.

Accommodation of the server and the private branch exchange in shielded rooms is also recommended if accommodation is not possible in the basement.

2.5.2.1.5 Cable ducts

The extensive RF, IF, audio, power and control cable connections required for interconnecting various components within the monitoring building and for cable circuits from antennas and other external facilities, make it common practice to incorporate cable ducts into the floor of the building. These ducts should be provided with frequent access openings to simplify installation and replacement of the various cables. Two types of floor duct are commonly used:

– an open-top duct with suitable removable continuous covers which, when installed, lie flush with the surface of the floor;

– enclosed ducts with screw-in caps at frequent intervals for access to the ducts.

The compatibility of materials should be considered when ducts are constructed, as from a metallurgical point of view, aluminium ductwork or cable tubes should, under no circumstances, be in direct contact with concrete.

It is suggested that incoming signal and control cables from antennas, DFs, and the transmitter building be routed to a terminal board at the point where the cables enter the building, with all incoming cables terminated at this board using appropriate connectors. This arrangement permits more rapid isolation of cable faults than is possible when the various cables are run directly to the equipment racks within the building. Also, it is not good engineering practice to run RF or audio cables in the same ductwork as power cables.

2.5.2.1.6 Building or room for emergency power plant

If the capacity of the emergency power plant is greater than a few kW, it should be installed on a floating base, which was cast separately from the surrounding floor to minimize the transmission of vibrations to the floor and the building itself. For larger plants, an underground fuel tank is desirable; it should be installed several metres away from the building to minimize fire hazards.

Depending on national safety regulations it can be mandatory or at least more cost effective to house the emergency power plant in a separate building. In both cases adequate fire protection arrangements should be made.

2.5.2.1.7 Machine shop, vehicle storage building

The requirement for this building will depend upon local conditions and the number and size of the vehicles. If petrol is to be stored for use in the vehicles, it is desirable that the fuel tank and pump be outside and separate from the building, to avoid undue fire hazards. Fire or excessive temperature-rise alarms should also be considered for this building.

2.5.2.2 Protective enclosures for remote, unattended monitoring operation

Protective enclosures, also known as equipment shelters, can be used to house radio monitoring and DF equipment for transportable stations and/or for remote, unattended operation. Such buildings should include the minimum space and power needed to support the equipment and casual local operation and maintenance activities. While protective enclosures are available in a variety of size and shapes, two types of typical enclosures are described here.

Type 1: Type 1 enclosures have the dimensions of a typical 19-inch equipment rack. They are constructed of sturdy, watertight materials, and include doors in front and rear for access to equipment. They include a cable entry panel. They typically have heating and air conditioning, placed on the ground next to the equipment, to provide cooling for the equipment.

Type 2: Type 2 enclosures have the dimensions of a small shelter. They are constructed of sturdy, watertight materials. They include an access door and have room for a maintenance person to access the front and back of equipment rack(s). They include an operator work area inside the shelter, consisting of a desk or table and

storage cabinet. They typically have heating and air conditioning, mounted on the shelter, to provide cooling for the equipment.

Both types of protective enclosures should have an uninterruptible power supply (UPS) with battery backup. They should include an automatic over-temperature shut-off, so the equipment is not damaged by excessive heating should the environmental control units fail. They should include remote status and alarm for power failure, ECU (Electronic Control Unit) failure, or condition of over/under temperature.

2.5.2.3 Utilities, power supplies and other installations

2.5.2.3.1 Electrical power

Where reliable and adequate electrical power is available from power sources external to the monitoring facility, it is usually preferable to obtain power for normal operations from such sources rather than to depend entirely on power generated in the station. If adequate power is not available from outside sources, and if uninterrupted operation of the monitoring station is required, two separate power plants of adequate capacity to handle the peak station load and with good voltage and frequency stability should be installed. Where an external source of power is used, a single emergency power plant will normally be sufficient to bridge the time gap when the external power supply is not available.

It is desirable to install all power distribution cables underground, to minimize the introduction of radio-frequency noise into the station. This is particularly important when high voltage transmission lines provide service to industrial or residential areas, since noise may be introduced into the local distribution lines from machinery connected to the outside line. By running the circuits underground within the confines of the monitoring station property, radiation from the lines will be negligible, and the capacitance between the lines and ground will tend to by-pass radio-frequency energy existing on the external lines. The routes of all underground power, communication and control cables should be carefully plotted and recorded, to avoid the likelihood of damage when excavations are made for antenna poles and structures.

Modern emergency power plants allow automatic switching between main and emergency power. With automatic switching, it is desirable to provide a time delay of a few seconds between disconnection of main power and activation of the emergency source to avoid repeated starting, stopping and switching arising from very short power failures.

2.5.2.3.2 Uninterruptible power system

Besides an emergency power plant, it is necessary to have an uninterruptible power system (UPS) in the monitoring station to support the computer system during the changeover intervals between normal power mains failure and starting the emergency generator. UPS systems convert DC to AC and normally operate from a dry cell or storage battery supply.

The UPS should have appropriate technical specifications (e.g. time delay for starting better than 5 ms, effective noise and surge features, and having the capability of running for a sufficiently long interval, i.e. more than 10 min) to prevent computer systems from losing information and having to be reset. This operating interval allows operators to save information and data that would otherwise be lost, and to manually start the emergency power generator in case of failure of the automatic start and changeover from power mains.

In the design phase of the UPS, it has to be decided which equipment will be powered by the UPS. The cost very much depends on the maximum power. Nevertheless, a reasonable reserve should be calculated.

2.5.2.3.3 Emergency lighting

It is necessary that the monitoring building and the emergency power plant building be provided with battery-operated emergency lights, which are automatically activated when the normal power supply to lighting circuits is interrupted. With this emergency lighting, station personnel can rapidly locate the emergency power plant controls and manually start the emergency generator, if needed.

The emergency lighting can be operated either by dry-cell batteries, which require periodic testing and replacement, or by wet cells which float on the normal electrical circuit and which are constantly charging.

2.5.2.3.4 Telecommunications

There is a constantly growing importance of properly working telecommunication connections with availability near to 100% for a radio monitoring service.

It would not be possible to adequately summarise in this Handbook the experience of operators and computer companies in this perpetually developing field. Therefore, the only advice given here is to dimension the communication architecture sufficiently to meet future requirements and consider the physical security of local data infrastructure, including ducts for reliable data cabling and the installation of servers in rooms or secure racks with restricted access.

2.5.2.3.5 Heating and air conditioning

Heating and air conditioning requirements will depend upon the local climate. It may be well to consider providing exhaust fans, together with air ducts extending from the tops of the monitoring equipment racks to the outside of the building. During cold weather the heat discharged from the monitoring equipment may be exhausted within the building to effect economies by reducing the demand on the normal heating system.

2.5.2.3.6 Fire warning and extinguishing systems

It is necessary for every monitoring station to be equipped with alarms and smoke detectors along with fire extinguishers appropriate for electrical fire, and a water sprinkler system throughout the building.

Large buildings typically require standpipes for connection to hoses by fire fighters.

2.5.2.4 Lightning protection

The purpose of lightning protection is to protect a vulnerable part of the spectrum monitoring station with minimum damage.

The lightning rod has been the front line of defence against the direct lightning strike.

For induced lightning, the total lightning protection plan for grounding, interconnection or bonding, shielding and surge suppression should be implemented.

2.5.2.4.1 Lightning effect

Lightning is the result of separation of charges in thunderclouds.

The maximum dumped current (power) of flash can amount to almost 400 KVA.

However, from the statistics, most dumped currents are less than 100 KVA, and about 50% of them are between 20 and 25 KVA; the range when the end of leader launches lightning stroke toward ground (stroke range) is between 30 m and 70 m for 20 KVA and between 70 m to 150 m for 50 KVA.

There are two categories of lightning effects known as:

a) Direct lightning strike that causes enormous damage due to a huge amount of lightning strike current. Normally conductor elements, e.g. building and antennas are exposed to this kind of effect.

b) Induced lightning effect caused by an intense electromagnetic field results in transient voltage and current surge in equipment and can affect actual strike up to several kilometres away.

2.5.2.4.2 Protection against direct lightning strike

This kind of protection is mainly for outdoor objects such as sheaths of buildings, antennas and power supplies.

The method for this process is to catch the main portion of lightning power and lead it into the ground.

To accomplish this, three main elements are important:

a) Lightning rod (air-termination): this is the first and front line of defence against the direct lightning strikes, which is intended to intercept a lightning stroke.

b) Down-conductor: an electrical conductor connecting the lightning rod to an Earth-termination. According to the existing standards, the most conductive metals (e.g. copper or aluminium) should be used for the down conductor.

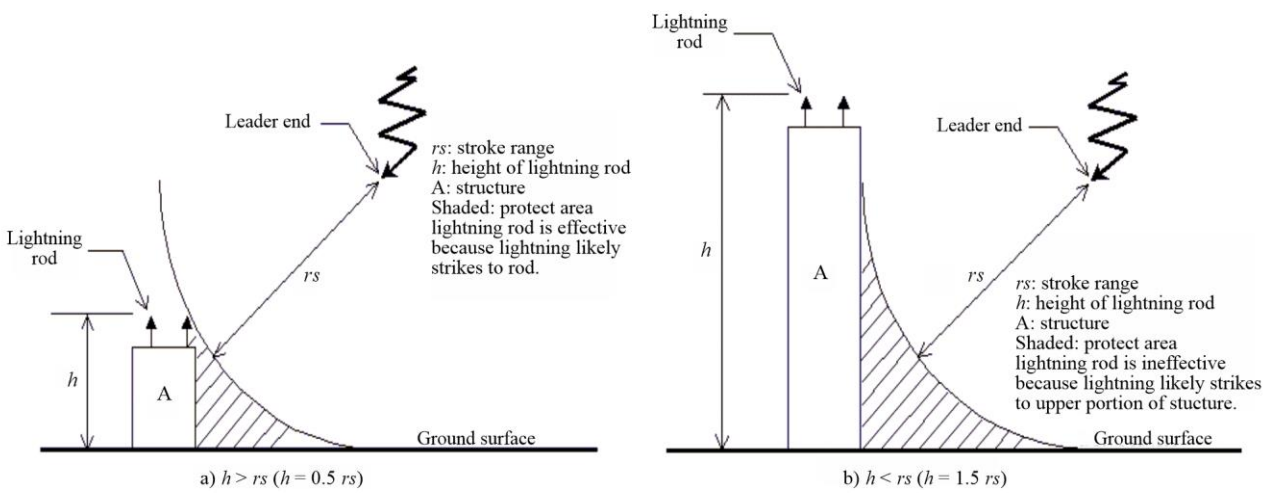
c) Earth-termination: a system of earth-electrodes (usually buried) intended to disperse lightning current into the earth.

As shown in Fig. 2-4, the extent of the protected area for a structure largely relies on the magnitude of stroke current (see § 2.5.2.4.1) and the height of the lightning rod.

When the height of the lightning rod is bigger than the stroke range (*hours*) as shown in Fig. 2-4 b), the lightning rod is ineffective in attracting the lightning; hence the lightning may strike the upper portion of the structure.

FIGURE 2-4

Protection area



HDB-23-2-4

Because the stroke range relies on the stroke current, IEC 62305-1 (Basic criteria of structure protection) defines four protection levels (from I to IV) of a structure. For each protection level, a set of maximum (IEC 623051-1 Table 3) and minimum (IEC 62305-1 Table 4) lightning current parameters is defined. The minimum values of lightning parameters are listed below.

Protection level	**Minimum peak current (kA)**	**Rolling sphere radius related to the minimum peak current (m)**
I	3	20
II	5	30
III	10	45
IV	16	60

From the cumulative frequency distribution of lightning current parameters, a weighted probability can be determined that the lightning current parameters are smaller than the maximum values and respectively greater than the minimum values defined for each protection level (see Table 2-3 below). The protection measures specified in IEC 62305-3 and IEC 62305-4 are effective against lightning whose current parameters are in the range defined by the protection level assumed for design.

TABLE 2-3

Probabilities for the limits of the lightning current parameters

Probability that lightning current parameters are	**Protection level**			
	I	**II**	**III**	**IV**
smaller than the maximum values of protection level	0.99	0.98	0.95	0.95
greater than the minimum values of the protection level	0.99	0.97	0.91	0.84

The lightning protection system with a lightning rod is not the complete system for protection against lightning strike. It is important to determine to what extent the spectrum monitoring station should be protected.

2.5.2.4.3 Protection against induced lightning

This kind of protection is mainly for indoor equipment, e.g. receivers, AC power supplies, including protection against direct lightning strokes. This protection could only be achieved by a careful investigation of the spectrum monitoring station to identify all sensitive equipment and all possible paths for the transient voltage and surge current. These should be followed by the design, specification, installation and maintenance of the protection system.

For designing the protection system, there are four engineering concepts of grounding, bonding, shielding and surge suppression.

– Proper grounding and bonding provide additional paths for lightning current that leads lightning current to the ground, thereby minimising surges. These include interconnecting equipment cabinets, individual components, grounding wires and may include interconnecting of adjacent conductors such as structural steel and conduit.

– Shielding of cables reduces surge by providing a preferential path for lightning current rather than the actual circuit. To be most effective, shielding should be completely continuous, and grounded or terminated.

– Surge suppression device provides a function to suppress transient voltage and surge current resulting in damage to the equipment interconnected by cables over long distance. It should be so selected that it can handle the voltage and current expected from severe induced lightning.

Effective protection includes the protection of all interfaces of the installation using one protection concept.

2.5.2.4.4 Protection process

Using a lightning rod for outdoor objects is necessary as the first step for protection of the building, but it is also necessary to limit the overvoltages on power sources, antennas and data lines before they reach at the electronic equipment.

All the lines (power and communication) and antenna feeders should enter the building at the same place.

In the entry point, all the lines should be connected to the equipotential network, so the cables, shields and other metal elements that do not carry signal or power are connected to the equipotential bonding bar directly.

Power and signal lines (from receiving antennas, direction finders or communication/computer lines) that carry signal or power are connected to the above-mentioned bar through their own special arresters. In such a case, the potential of all lines will increase equally and simultaneously and therefore the difference of potential (between signal lines and shields) trends to zero during the lightning period.

The residual voltages or the overvoltages resulting from the length of the conductor (from entry point to the equipment location) induced by electromagnetic signals should be omitted by inserting a finer protector at the point nearest to the equipment.

It is noteworthy that a protector device by itself cannot provide full protection; the most suitable protective devices should be used in several phases, according to the specifications of the equipment.

2.5.2.4.5 Earthing and screening

Effective and secure earthing is an essential factor for lightning protection procedure and shall comply with IEC 62305 standards.

It is recommended that suitable measures be taken already in the planning phase. All metal parts of significant dimensions associated with the structure shall be bonded together and to the lightning protection system, e.g. metal reinforcements of concrete or metal skin roofs and metal facades.

Bonding shall be carried out for all external conductive parts entering the structure. In larger structures like monitoring centres, the connection to copper internal ring conductors is a good solution. Adequate bonding of cable shields is an essential part of the lightning protection zone concept. Basically, all shields should be bonded at both ends – at the patch panel as well as at the terminal/socket – directly or indirectly via surge protection devices. It is beneficial to have many parallel paths to reduce the injected currents in the cables and shields. A meshed earthing system fulfils this requirement.

Bonding shall be provided and installed at the boundary of lightning protection zones (LPZs) for metal parts and systems crossing boundaries, all by an equipotential bonding bar that should be connected to the electrodes of the earthing system.

The contact and bedding resistance of the ground can be reduced by appropriate measures, termed "earthing improvement", such as increasing the soil conductivity by injection high-conducting solutions and thereby reducing the contact and bedding resistance. One example is hygroscopic emulsion that has been developed for this purpose.

The earthing network should be clean with a minimum resistance of 4-10 Ω or better. Metallic parts should be anti-corrosive with high conductivity. According to the climate conditions, soil composition, humidity and quality of materials applied in, the earthing system should be tested and improved at regular periods of time. The ground connection itself should be short and include buried plates to minimise the impedance.

2.5.2.4.6 Antenna protections

Besides earthing and outdoor protection measures the following also should be considered:

– The antenna system/array should be brought within the 45° protection area, and/or rolling sphere protection radius of the lightning rod.
– The lightning rod should be mounted vertically above the antenna system/array or, if not possible, it may be mounted in the vicinity of the system so as to make a proper protection area around the system.
– The air-termination and down-conductor should be mounted in such a way to retain the antenna array symmetry.
– In regions with a high rate of lightning, it is preferred that the antenna be disconnected from the equipment, if a prediction of the lightning time is possible.
– To cover the antenna surface by proper insulations (e.g. fibreglass materials).
– For active antennas, appropriate arresters should be used to allow DC voltage to pass, due to normal operation of the antenna systems.
– Antenna masts/towers should be earthed to the best advantage.
– Shields of RF and coaxial cables should be earthed properly and in the case of high mounted antennas, these shields should be bonded to the antenna mast at the top and bottom ends.

2.5.2.4.7 Maintenance of lightning protection system

Maintenance of the lightning protection system is sometimes disregarded because lightning protection systems are not counted among the main equipment. Scheduled maintenance is indispensable to the lightning protection in order to limit damages when the lightning strikes. In particular, the lightning rod and the down conductor

installed outside the structure should be well maintained to avoid chipping due to lightning and rust. The grounding resistance should also be kept continuously under watch.

IEC 62305-3 recommends a maximum period between visual inspections of one year for lightning protection systems of level I and II, and two years for level III and IV while a maximum period between complete inspection of two years for protection level I and II and four years for level III and IV. A complete inspection on annual basis is instead recommended for critical structures where a high number of people may be present, such as commercial buildings or offices.

2.5.3 Sources of interference affecting the operation of monitoring stations

2.5.3.1 General principles

As far as possible transmitters of any kind should be excluded from a monitoring site. If, however, it is necessary to accommodate such equipment for good reasons, e.g. communication purposes like cellular UE or indoor Wi-Fi base station, care should be taken at the planning and installation stage to avoid or minimise negative impacts on the monitoring process.

More commonly, interference arises from equipment radiating RF energy unintentionally. There are basically two main interference mechanisms: radiation and conduction. Radiation can occur either directly (due to insufficient or faulty screening of the source) or via connecting cables. Interference can arise also via an antenna if the frequency of the radiated signal falls within the operational band(s) in use at the station.

However, if the source of interfering radiation is outside the casing of a piece of monitoring equipment, interference may or may not occur depending upon the effectiveness of the equipment screening. Similarly, radiation in or outside a cable run may or may not cause interference depending upon the effectiveness of the screening of the cable run and the way it is laid.

Conduction of interference from an offending source can either be mains-borne or by control and signal cables used for inter-connection purposes.

2.5.3.2 Sources of interference

These are as follows:

– PCs and servers, including their peripheral devices (monitors, printers, scanners, cabling, etc.) used for office applications and device control;

– telephone exchanges, IP routers, IP switches, mobile telephone terminals, cordless telephones;

– fluorescent lamps;

– halogen lamp power supplies;

– solid-state switches used in power supplies, heating/air-conditioning and other control equipment;

– electric motors used for fans and ventilators (kitchen, offices), vacuum cleaners and antenna rotors;

– vehicles and lawnmowers with spark ignited engines;

– ISM equipment (microwave oven);

– indoor Wi-Fi base stations;

– cable TV and similar cable distribution systems.

2.5.3.3 Remedial action

All metallic services entering the sensitive areas should be separately earthed in a manner that also complies with local electrical safety regulations. The merits of non-metallic barriers can be considered but if metal is used inside the sensitive area, it should again be suitably earthed.

RF cabling should be separate from all other cables in the console and securely earthed. Interference caused by telephone and intercom cables may often sufficiently be reduced, e.g. by passing the cables, e.g. five times through four rings.

PCs are ubiquitous and cannot be excluded from the operations room. Therefore, low radiation types should be procured. Some caution should be exercised in relation to tempest specified devices since they only guarantee that the radiation does not contain any information rather than low radiation.

LANS and similar interconnections should be based on fibre-optic cabling rather than copper. This will avoid any radiation and also avoid unintentional earth loops. The signals of the station frequency standard should also be distributed to the consoles using fibre-optic cables for the same reasons.

If the proximity of data cables and RF or audio cables is unavoidable, double screened cables should be used. Audio cables should be tightly twisted and screened or double screened.

Normally radio-monitoring equipment has adequate radiation properties. Some care may be required however, if radio amateur equipment is used.

Purely data processing or switching devices, which do not need to be manned by the operator, should be in a separate, adjacent cabinet if possible.

Effective and secure earthing and screening is essential not only for lightning protection but also for the reduction of RF interference. For more details about earthing refer to § 2.5.2.4.5.

These precautions are relatively simple if considered at the installation phase. Subsequent identification and elimination of discovered problems can be protracted and costly.

2.5.4 Site survey

Before installing the spectrum monitoring system, a comprehensive evaluation of the operational tasks, the required geographical coverage, the radio conditions and other limitations should be made. The priority of all relevant items should be clear and written in a document.

Following this, a site survey should be undertaken using a checklist adapted to the requirements. Normally the site evaluation will show that most of the surveyed sites will not meet all requirements and compromises cannot be avoided.

The results of the evaluation should be summarised in a comprehensive report. The report and the attached checklist should be kept as reference for the future.

The example of a site survey checklist and a comprehensive evaluation report form is contained in the Annex 1 to Section 2.5.

Annex 1
to Section 2.5

Site survey checklist

Ref. No.:		Prepared by:			Date: / /
0	Site name	□ New □ Existing			
1	Site address				
2	Proprietor				
3	Consent of proprietor for installation	□ Agreed with no requirements			
		□ Agreed under condition of:			
		□ Disagreed with refusal of site survey			
3	Address				
4	TEL/ /mail address	/			
5	Building (With pictures)	Form		Height from ground surface	Elevation of ground surface from MSL
		□ Building □ Tower ( ) □ Others ( )			
				Frequency:	
				Distance:	
				Remarks	
7	Surrounding area (with pictures)				
8	Geographical position	Latitude (degrees, min, s)	°N ’’’		
		Longitude (degrees, min, s)	°E ’’’		
		UTM (zone, North, East)			
		Datum used			
		Method and Source	□ GPS / □ Map		
		Elevation AMSL (m)	“x” m		
		Accuracy of determination X,Y,Z:	“x” m		
		Positioning on map (file or paper)			
		Map reference	map code:		
		Projection system on map	Cylindrical, Lambert conical, polyconical, gnomonic: xxx		
		Site sketch	See attachment No. x		
		Photographs	□ Yes, see attachment No.		
			□ No		
9	Site environment	Temperature range (°C):	Minimum	Maximum	

		Deforestation required:	□ Yes		□ No
		Moisture content (%):			
		Storm water	□ Yes		□ No
		Snow (cm)	Minimum		Maximum
		Seismic risk:	□ No		□ Yes, value (Richter range):
		Remarks:			
10	Antenna location	Location	See attachment No.		
		Coordinate	See attachment No.		
		Elevation against surrounding obstruction	□ highest (with picture)		
			□ not highest but good enough (with picture)		
			□ lower (with picture)		
		Elevation	From ground surface:		
		Other antenna	□ No		
			□ Yes	Classification:	
				Polarisation:	
				Distance:	
		Overhead line	□ No		
			□ Yes	Classification:	
				Distance:	
		Resonant object	□ No		
			□ Yes	Classification:	
				Distance:	
		RF field strength	Frequency:		
			Field strength:	See attached sheet 3	
11	HFDF Antenna	Land available for array diameter plus guy wire extension area		□ Yes	□ No
		Flatness of the land; 3° gradual slope for the site is acceptable from one side of the antenna to the other			
		The vertical clearance is better than 3° for TOA			
		Soil bearing for the antenna support			
		Identify potential scatters such as tall buildings, big trees, high voltage transmission lines, radio towers, etc.			
		Potential scatters need to be at least as far away as specified in Table 2-1 from any antenna element			

11	HFDF Antenna (cont.)	Scattering free environment for inside the antenna array				
		High voltage power lines need to be away from the antenna array, see Table 2-1				
		Equipment needed; camera, theodolite with magnetic compass, 100- or 300-foot tape measure, 12-foot tape measure, GPS binoculars, spectrum analyser and field strength meter; obtain site contour map if possible			Should be prepared before site survey	
		Corrosive or wet environment conditions			□ Good	□ Not good
		Ground conductivity should be measured			□ Good	□ Not good
					□	
12	Radio technical aspects	Coverage area	See attachment No:			
		Existence of nearby radio station including planned	□ Yes	□ No	Name:	
					Frequency:	
					Field strength:	
					Distance:	
					Remarks:	
		Nearby high-power unwanted emitters	Transmitter name			
			Transmitter service			
			Frequency (MHz)			
			Field strength (dBμV/m)			
			Saturation or interference			
			Distance (km)			
		Natural/man-made noise sources	Threshold	μV/m, mV/m, dBμV/m		
			Acceptable noise level to determined	□ Yes	□ No	
		Measurements of wanted emitters and controlled emissions	See attachment No:			
13	Structural strength for antenna installation	□ Sufficient (provided with structural strength calculation)				
		□ Structural strength calculation required				
14	Receiver equipment room	□ Existing	See attachment No.			
		□ None	Room proposed			
			Remarks			
15	Structural strength for receiver installation	□ Sufficient (provided with structural strength calculation)				
		□ Structural strength calculation required				

16	AC power	□ Provided		
		□ Not provided	□ Alternative power source available:	
			□ No power source available	
17	Data communication media	□ Provided	Classification:	
			Cable route:	See attachment No.
		□ Not provided	Alteration:	
18	Required materials for installation	Antenna system		
		Receiver system		
		Removal of any		
		Grounding system		
		Obstruction height		
		Lightning protection		
		Special requirements if any		
19	Accessibility	Vehicle	□ Yes	□ No
		Heavy duty vehicle	□ Yes	□ No
		Parking lot		
20	Foundation work		□ Yes	□ No
21	Working environment	Working hours	□ No restriction	
			□ Restricted	
		Transporting equipment	□ No restriction	
			□ Restricted	
		Noise	□ No restriction	
			□ Restricted	
		Lighting	□ Not required	
			□ Required	
		Materials keeping space	□ Not available	
			□ Available	
		Working space	□ Not available	
			□ Available	
		Special condition		
22	Special requirements of proprietor	For installation		
		For installation work		

Comprehensive evaluation report

Prepared by:	Date: / /
Site name	
Reference number of site survey checklist	
Result of evaluation	□ Good □ Good with condition □ Cancelled
Background of evaluation	□ Installation cancelled by proprietor's refusal
	□ Inappropriate siting because of:
	□ Others
Remarks	

2.6 Personnel

2.6.1 General

Despite the automation of measurements as made possible by processors, the most important – and in many countries, most expensive – resource remains personnel. Careful planning is required to guarantee the continued availability of an adequate number of properly qualified staff.

The number of staff and the qualifications required depend on a variety of factors, including the tasks of the monitoring service, the degree of automation of the technical facilities, and the number of sites and vehicles.

The age structure of the personnel should provide older staff with long-standing experience in the field of radiocommunications and younger staff with up-to-date IT knowledge. With only older, experienced workers, the monitoring service would risk losing its expertise within a short period of time owing to staff retirement. Equally, it would make little sense to have only young workers with up-to-date IT know-how but no experience in the field of radiocommunications and wave propagation. In addition, a mixed age structure has an advantage in that staffs have opportunities for promotion.

2.6.2 Categories of personnel

The personnel of a monitoring service can be categorised as follows:

– management;

– operators;

– technical/maintenance service;

– clerical staff.

2.6.2.1 Management

The personnel with managerial tasks include monitoring station managers and staff responsible for fundamental decisions relating to the organization and facilities of the monitoring service. The management staff needs skills in the following areas:

– structure and procedures within the administration;

– operational procedures and technical knowledge in the monitoring stations and equipment;

– Radio Frequency technology;

– economic interrelationships;

– ITU-R knowledge of RR, Resolutions, Recommendations and Reports

– law.

Station managers should have preferably worked as operators or technical staff at monitoring stations.

2.6.2.2 Operators

Operators perform the monitoring tasks and need to be familiar with the administrative regulations for radiocommunication services as well as the technical equipment. In view of the increasing use of automated monitoring systems and software, they also need IT know-how. Both engineers and technicians are therefore suitably qualified to work as operators, gaining specialized knowledge of the radiocommunication sector mainly through on-the-job training.

2.6.2.3 Technical/maintenance service

Appropriately qualified operators may occasionally perform technical tasks, including installing and maintaining equipment, in the smaller stations and vehicles. However, it is more practical to have separate staff so that operators can focus on their monitoring tasks. Staff that is only responsible for maintenance do not need any special knowledge of the individual radiocommunication services.

2.6.2.4 Clerical staff

Clerical staff should be familiar with standard PC software, including word processing and spreadsheet programmes.

2.6.3 Training

2.6.3.1 Introduction

Quality can only be created by staff who are properly trained and motivated. Training is therefore essential to prepare staff for their duties. It widens their knowledge, complements their skills and refreshes their background.

The technology of radiocommunication systems and hence of spectrum monitoring equipment is evolving rapidly. Considering that the issues at stake are also changing rapidly, it is necessary to factor in changes in national and international regulations, too; these changes strongly affect, directly or indirectly, spectrum monitoring activities. Training should therefore be understood as a continuous, open-ended process.

2.6.3.1.1 Identifying requirements and planning the course

Training requirements can be defined as the difference between the target and the actual qualifications that the staffs possess. Before identification can take place, it is therefore important to clearly define the workplace requirements, to make an objective assessment of actual qualifications, taking account of future requirements as well. In one-to-one talks with staff, managers should find out what training requests/wishes exist, and establish the requirements accordingly. Training is a management function.

As far as planning is concerned, it is important to pinpoint the deficit and to define the knowledge and skills that the course is to impart. Only when this is done can “training tourism”, bad investment and poor motivation be avoided.

Afterwards the following questions should be answered:

– What are the aims and content of the course, what knowledge and skills are desired to be imparted?
– What qualifications do the participants already have in this field? (Among the spectrum monitoring staff a wide range of educational degrees can be found.)
– Is the course intended to start from scratch, to provide retraining, to be a refresher course or to lead to a special qualification?
– Is it to be a technical, an IT, a foreign language, an administrative or a management course?
– Does the organization have suitable staff of its own to hold courses, or should this be done by private companies, consultants or manufacturers?
– What media/teaching aids (paper, videos, simulators, exercises, interactive software, etc.) are to be used?
– Are syllabuses and course material available?

– What is the maximum number of participants for training to be effective?

– Does the course need to be held in a particular place?

Once these questions have been answered it can be decided whether in-house or external training is appropriate, how long the course should last, what the timetable should be and who will compile the course material. Often it is not possible, however, to provide training on the scale required because of, budget constraints. In this case priorities must be set, whereby a consensus should be sought with all concerned.

As soon as the planning has been finalised, instructors and instructees should be given timely notification in order to make their preparations.

2.6.3.1.2 Review and evaluation

The review and evaluation is a very important step in the process. The importance of this step is sometimes underestimated. At the end of the course it should be checked whether the course was carried out as planned and whether the goals were achieved. For this purpose, participants should complete a questionnaire assessing the training received. The following questions, for instance, could be asked:

– Was the course helpful for your day-to-day activities?

– How do you rate the material provided?

– How do you rate the instructors?

– How do you rate the technical/specialist content?

– Was the course well organized?

– How do you rate the venue?

– How do you rate the course overall?

– If you had to prepare and hold the course yourself, what would you do better?

The evaluation could also include a poll of participants after about three months, inquiring whether they had been able to use what they had learnt, whether they had passed on to their colleagues what they had learnt and whether they considered the course aims had been achieved.

2.6.3.1.3 Correction measures

The assessment input provided by the participants and their superiors, too, feeds into the planning of further courses. This closes the circle.

2.6.3.2 Training methods and implementations

There are different possibilities how to implement the training. Some Administrations do the training by themselves with their own facilities and staff. Others prefer to hire private companies, consultants or manufactures to perform the training.

Besides attending theoretical and practical courses, including the use of simulators and interactive software, it is essential for the personnel to read books, articles, documentation and ITU-R Handbooks, Reports and Recommendations; exchange information and experience with other colleagues, both national and from other Administrations, is important.

As part of the overall training strategy, on the job training is the most effective and frequently used form of training for new staff. It is a key method to preserve the know-how of the department. Yet it is not enough simply to assign new members of staff to an experienced colleague and trust that all will be well. It is the responsibility of the manager to plan on the job training and to monitor progress.

2.6.3.3 Skills required of the spectrum monitoring staff

The radio monitoring service copes with a wide range of radio services, systems and administrative procedures which continuously evolve and are subject to updates. Therefore, there is the need for updated knowledge in all the relevant procedures and systems involved in the spectrum monitoring (e.g. digital modulation schemes, data engineering, international and national spectrum regulation) as well as the preservation of already existing knowledge (e.g. analogue modulations, legacy measurement equipment and procedures). There are differences

between countries in respect of their legal systems, administrative structures, educational systems and frequency management systems, for instance. Also, the skills required of the spectrum monitoring staff depend on their specific tasks. Hence it is not possible to specify a common, comprehensive syllabus for the skills required.

For this reason, the items listed in Annex 1 are only suggested theoretical and practical items for inclusion in training programmes and courses directly relevant to spectrum monitoring staff. A theoretical basic knowledge of mathematics, physics and language, along with a fluent ability in calculations in logarithmic units is assumed.

2.6.3.4 Worldwide available training facilities for radio monitoring

Training is very much connected to the actual type of equipment, which can be significantly specialized; however, it is worth mentioning here below some institutions and industrial facilities that offer training in the field of radio monitoring. Both the ITU Telecommunication Development Bureau (BDT) and Radiocommunication Bureau (BR) provide training opportunities as described below, and the BDT can provide guidance to developing countries regarding specific courses and possible sources of funding to attend those courses, including sources of funding for both training costs and travel/living expenses.

As a means of promoting and developing monitoring systems, the Administrations of Germany (Federal Republic of), Australia, Canada, China (People's Republic of), Korea (Republic of), the United States of America, France, Hungary, Israel (State of), Italy, Japan, Netherlands (Kingdom of the), Portugal and the United Kingdom of Great Britain and Northern Ireland have offered in Resolution ITU-R 23 (Note 1) to receive monitoring officials from other Administrations. Initial contact to arrange such training may be made to the appropriate Central Office as defined by RR Article **16** and as shown in List VIII (List of Monitoring Stations) published periodically by the ITU.

Additionally, training is also provided by several manufacturers and vendors of monitoring equipment themselves.

2.6.3.4.1 Training provided by ITU

ITU offers several programmes provided for training which include resources such as the ITU Academy, workshops, or seminars.

The ITU Academy is the main online gateway to ITU's capacity development activities which brings together a wide range of training activities and knowledge resources in the field of information and communication technologies (ICTs) and digital development. It consists of an e-learning platform with a large selection of training courses on different modalities (online self-paced, online instructor-led, face-to-face, and blended) and a content management system featuring information on ITU's capacity development activities such as training courses, workshops and seminars, publications, and training material.

Spectrum monitoring training is provided by the ITU Academy as part of the Spectrum Management Training Programme (SMTP), which comprises a set of high-level training materials in all areas of spectrum management designed for Member States and Sector Members of ITU, in collaboration with experts from within and outside ITU. SMTP is available to anyone who would like to enhance and broaden their professional knowledge while working in the field of spectrum management. Spectrum Monitoring module covers the role, functions and basic techniques of spectrum monitoring, and purpose and capabilities of different types of spectrum monitoring equipment. The course is targeted at engineers and officers tasked with planning, engineering, monitoring, and operation of radio systems in developing and least developed countries.

2.6.3.4.2 Training facilities in the United States of America

Within the United States of America, the United States Telecommunications Training Institute (USTTI) has been offering tuition-free training opportunities in radio monitoring and related spectrum management activities since 1983, after the Institute was launched at the ITU Plenipotentiary Conference in Nairobi, Kenya. Each year the USTTI offers a number of courses related to radio monitoring, radio spectrum management, or radio measurements:

– Radio frequency spectrum management (annually).

– Spectrum management in the civil sector (annually).
– Radio spectrum monitoring and measuring (annually).
– Modern spectrum monitoring and management techniques (annually).
– Radio spectrum monitoring techniques and procedures (annually).
– Laboratory techniques in support of equipment authorisation programmes (annually).

In addition to these opportunities, as described below, U.S. companies sponsor USTTI wireless radiocommunication courses, which may contain elements of spectrum management. Details of these are available via the USTTI website – ustti.org. Training under the aegis of the USTTI is tuition-free.

USTTI course on radio frequency spectrum management: this course, lasting two weeks, addresses the various elements required to plan, organize, manage, and control an effective spectrum management agency with the developing nation in mind. Participants are introduced to spectrum management principles, national spectrum planning and policy, engineering analysis, and computer-aided techniques. In addition, the course will introduce technological and regulatory changes that have taken place in recent years.

USTTI course on spectrum management in the civil sector: this course, lasting two weeks, is intended to provide information and material for the national civilian telecommunications spectrum manager to enable logical, spectrum-related decisions that are well grounded in basic technical procedure.

USTTI course on radio spectrum monitoring and measuring: this course, lasting one week, at a field facility of the Federal Communications Commission (FCC) will address: Fixed and Mobile direction finding; Spectrum Measurement Software; and Satellite Monitoring from an equipped satellite console using a large Cassegrain feed parabolic antenna. The course will also discuss methods for spectrum monitoring, including record and playback of spectrum for time continuous spectrum analysis.

USTTI course on modern spectrum monitoring and management techniques: this one-week course covers ITU-compliant techniques for spectrum monitoring and management. It combines classroom instruction with hands-on training to address modern challenges in the field. Topics include operational principles, system components, signal measurement, direction finding, and signal identification. Practical exercises involve mission planning, setup, execution, and data analysis using fixed, mobile, and transportable stations. More information on this USTTI course can be obtained from its sponsor, TCI, an SPX Company.

USTTI course on radio spectrum monitoring techniques and procedures: this course provides basic, practical instruction in the procedures of off-the-air technical measurements and radio direction finding for frequencies in the 30 MHz to 3 GHz range.

USTTI course on laboratory techniques in support of equipment authorisation programmes: this one-week course is intended to give participants hands-on training and experience in a functioning laboratory environment in making technical measurements, and in the testing and calibration of telecommunications equipment.

2.6.3.4.3 International training programme for spectrum monitoring in Japan

The Ministry of Internal Affairs and Communications (MIC) has international training schemes for spectrum monitoring.

This international training programme is executed by JICA (Japan International Cooperation Agency) for the developing countries in cooperation with MIC based on the needs of the participating countries. This programme is operated by ODA (Official Development Assistance) of Japan. More detailed information can be obtained from MIC or JICA.

2.6.3.4.4 International training programs of radio monitoring in Korea (Rep. of)

The Ministry of Science and ICT and the National IT Industry Promotion Agency (NIPA) of South Korea are operating the K-LINK program, an ICT-focused international training initiative for developing countries. Its primary goal is to share Korea's digital transformation experiences and ICT capabilities to strengthen participants' technical and policy skills while fostering bilateral cooperation and international networks.

Participants typically include government officials, engineers, and professionals from the telecommunications and spectrum management sectors, nominated by their respective countries or institutions. The program

usually runs as an intensive short-term course lasting around seven to ten days, combining lectures, hands-on training, visits to companies and research institutions, and cultural experiences.

The Central Radio Management Service (CRMS) under the Ministry of Science and ICT supports the training programme through lectures, introductions to spectrum monitoring facilities, and on-site discussions of current spectrum monitoring issues.

K-LINK encourages networking among participants, promoting international collaboration and experience sharing to improve the competitiveness of developing countries in the global ICT landscape.
The programme also provides support for airfare, accommodation and living expenses to ensure participants can fully engage in the training.

Meanwhile, since 2022, the Central Radio Management Office has hosted the Global Spectrum Management Forum, providing a platform where spectrum management authorities, international organizations, industry leaders, and academic experts from around the world gather both online and offline to discuss the present and future of spectrum management.

The forum addresses key topics such as the efficient use of spectrum resources, responses to illegal transmissions and interference, spectrum policies for emerging technologies, and strategies to strengthen international cooperation frameworks.

Participants share national case studies and technological trends, seeking collaborative approaches to build a sustainable spectrum environment.

Annex 1
to Section 2.6

Aspects of spectrum monitoring training

Organizational and general

– Structure, functions and common procedures
– Structure, functions and procedures of the national organizations relevant to frequency management and monitoring (e.g. aeronautical authority, maritime authority, police)
– Structure, functions and procedures of the relevant regional and international organizations.

Regulatory Frameworks

– Laws applicable
– Ordinances
– Agreements
– Regulation and standards.

Spectrum management

– Spectrum allocation tables, national, regional and ITU Radio Regulations
– Frequency assignment and licensing procedures
– Designation of emissions
– International Frequency List (IFL)
– Call signs
– Frequency re-use concept.

Basic radio theory

– Radio services, systems, and applications
– Propagation of electromagnetic waves, free space loss, effects of multipath propagation, link budget calculations
– Antennas: theory, types and techniques in each frequency range, antennas for monitoring stations.
– RF Transmitters including unwanted emissions
– Receivers: spectrum monitoring receivers, noise factor and signal to noise ratio, noise temperature; sensitivity and immunity, intercept points
– Modulation techniques, necessary bandwidth
– e.i.r.p. calculations and computer programs comparing measured to calculated levels
– Fourier Transform and Fast Fourier Transform (FFT)
– Filtering and shielding.

Measurement procedures

– ITU Recommendations, Reports, Handbooks as appropriate
– Frequency, frequency offset, frequency deviation
– Occupied bandwidth, spurious and out of band domains
– Field strength and power flux-density (pfd)
– Radio direction finding, quality of triangulation
– Identification of stations
– Selection of measurement points
– Registration, analysis, decoding.

Data management and ICT

– Databases
– Procedures and languages to query database and collect information of interest
– Statistics
– Data analysis and estimation
– Data science and engineering
– Cloud computing
– Artificial intelligence.

Practical aspects

– Reporting and data presentation including the production of reports of infringement and harmful interference, in compliance with the RR
– Procedures to identify TV interference sources, distinguishing between a faulty or wrongly tuned TV set, a spoiled amplifier power supply, a damaged cable or antenna joining, a damaged or saturated antenna amplifier, a multipath antenna orientation, an AM interfering emission, an FM interfering emission, industrial, scientific or medical apparatus in the vicinity, Short Range Devices, other electronic devices, etc.
– Procedures to identify possible elements where an intermodulation product is generated, as a faulty contact, etc.
– Procedures to monitor various radio services
– Selection of measurement points for mobile monitoring stations
– Recognising and reducing RF interference; main measures to be taken against harmful interference
– Aural identification of signals
– Fingerprint measurements

– Recognition of spread spectrum systems such as Frequency Hoppers and Direct Sequence

– Use of spectrum analysers.

References

ITU-R publications

NOTE – In every case the latest edition should be used.

Resolution ITU-R 23 – Extension of the International Monitoring System to a worldwide scale

Handbook on National Spectrum Management

ITU-R Recommendations

Recommendation ITU-R SM.575 – *Protection of fixed monitoring stations against interference from nearby or strong transmitters*

Recommendation ITU-R SM.1139 – *International monitoring system*

Recommendation ITU-R SM.2060 – *Test procedure for measuring direction finder accuracy*

Recommendation ITU-R SM.2097 – *On-site accuracy measurements of a fixed DF system*

Recommendation ITU-R SM.2140 – *Performance evaluation of mobile direction finders in operational environment*

ITU-R Reports

Report ITU-R BT.2142 – *The effect of the scattering of digital television signals from a wind turbine*

Report ITU-R SM.2181 – *Use of Appendix **10** of the Radio Regulations to convey information related to emissions from both GSO and non-GSO space stations including geolocation information*

Report ITU-R SM.2182 – *Measurement facilities available for the measurement of emissions from both GSO and non-GSO space stations*

Report ITU-R SM.2354 – *Alternative test procedure for measuring accuracy and immunity of direction finder using a simulator*

Report ITU-R SM.2356 – *Procedures for planning and optimization of spectrum-monitoring networks in the VHF/UHF frequency range*

Report ITU-R SM.2391 – *The effects of wind turbines on fixed radio direction finders*

Report ITU-R SM.2451 – *Assessment of impact on radiocommunication services from wireless power transmission for electric vehicle operating below 30 MHz*

CHAPTER 3

Monitoring stations and equipment

TABLE OF CONTENTS

Page

3.1 Introduction 81

3.1.1 General considerations 81

3.1.2 Station equipment networks 82

3.2 Types of monitoring station 83

3.2.1 Fixed monitoring stations 83

3.2.2 Mobile monitoring stations 87

3.2.3 Transportable monitoring stations 103

3.2.4 Additional support equipment 104

3.3 Monitoring and measurement antennas 106

3.3.1 General considerations 106

3.3.2 Influence of interference environment 107

3.3.3 Suitable antenna configurations 107

3.3.4 Antennas for VLF, LF, MF and HF 108

3.3.5 Antennas for VHF, UHF and SHF 115

3.3.6 Siting of antennas 123

3.3.7 Transmission lines and distribution systems 126

References 127

Bibliography 127

3.4 Monitoring receivers 128

3.4.1 General considerations 128

3.4.2 RF Front-end / Tuner 129

3.4.3 Digital Processing Sections 130

3.4.4 Frequency reference sources for receivers 132

3.4.5 Key performance characteristics of monitoring receivers 132

3.4.6 Specifications for typical monitoring receivers 134

References 139

Page

3.5 Direction finders 139

3.5.1 General considerations 139

3.5.2 Antennas 140

3.5.3 Equipment 140

3.5.4 Number of receivers 141

3.5.5 Bearing processing 143

3.5.6 Typical specifications for DF systems 143

3.6 Additional measuring equipment and standards 145

3.6.1 Time and frequency standards 146

3.6.2 Spectrum analysers 146

3.6.3 Handheld (HH) Vector network analyser (VNA) and cable antenna tester .. 151

3.7 Digital signal processing equipment and associated software 152

3.7.1 Introduction 152

3.7.2 Station functions 153

3.7.3 Monitoring station equipment and operation 155

3.7.4 Typical modes of equipment operation 156

3.7.5 Examples of equipment operation 159

3.7.6 Automatic violation detection 164

3.7.7 Reports in DSP-based systems 165

3.8 Equipment data interface 166

3.8.1 Data connections 166

3.8.2 Instrument control protocols 167

3.8.3 Controller host access and data transfer 169

References 171

Bibliography 172

3.1 Introduction

3.1.1 General considerations

The equipment available at a radio monitoring station should be suitable to perform the measurements required at that station. The measurements are derived from the tasks that the station has been assigned. These tasks in turn depend on the purpose and goals of radio monitoring within the country as covered in § 1.3. The nature and quality of the measurements will determine which types of equipment are necessary.

A monitoring station that will take part in the international monitoring system should be able to carry out the measurements with an accuracy that complies with the technical standards for monitoring stations contained within the relevant ITU-R Recommendations. Where applicable, these Recommendations are mentioned in the appropriate sections of this Chapter. Other characteristics of the equipment should meet the minimum criteria as stated in the relevant parts of §§ 3.3 to 3.7. Particular attention should be paid to provide recommended linearity for measurement receivers and active antennas as discussed in § 3.3.2 and to take into account the effect of the environment, such as surrounding metallic structures.

For a monitoring station, a minimum set of equipment would be a receiver and an antenna system for the frequency range of interest. A rotatable directional antenna can provide coarse bearing information. Basic frequency and field-strength measurement capability is also required and may be provided by using a calibrated receiver and antenna.

Monitoring systems often include a process controller to provide automation and local data storage capabilities allowing for a robust operation. Most monitoring stations use automation to relieve the operators from performing time-consuming, long-term measurements such as conducting spectrum occupancy measurements.

The most sophisticated monitoring systems consist of a hierarchy of national, regional, remote and mobile monitoring stations networked together to provide integrated real-time control of multiple stations from a single operation console. This type of system is computer-and network-based, using sophisticated software to relieve the operators of tedious tasks and greatly increase measurement speed. It also increases equipment utilization by allowing background tasks, such as searching for unlicensed transmitters, to be automatically executed when the equipment is not required for other purposes.

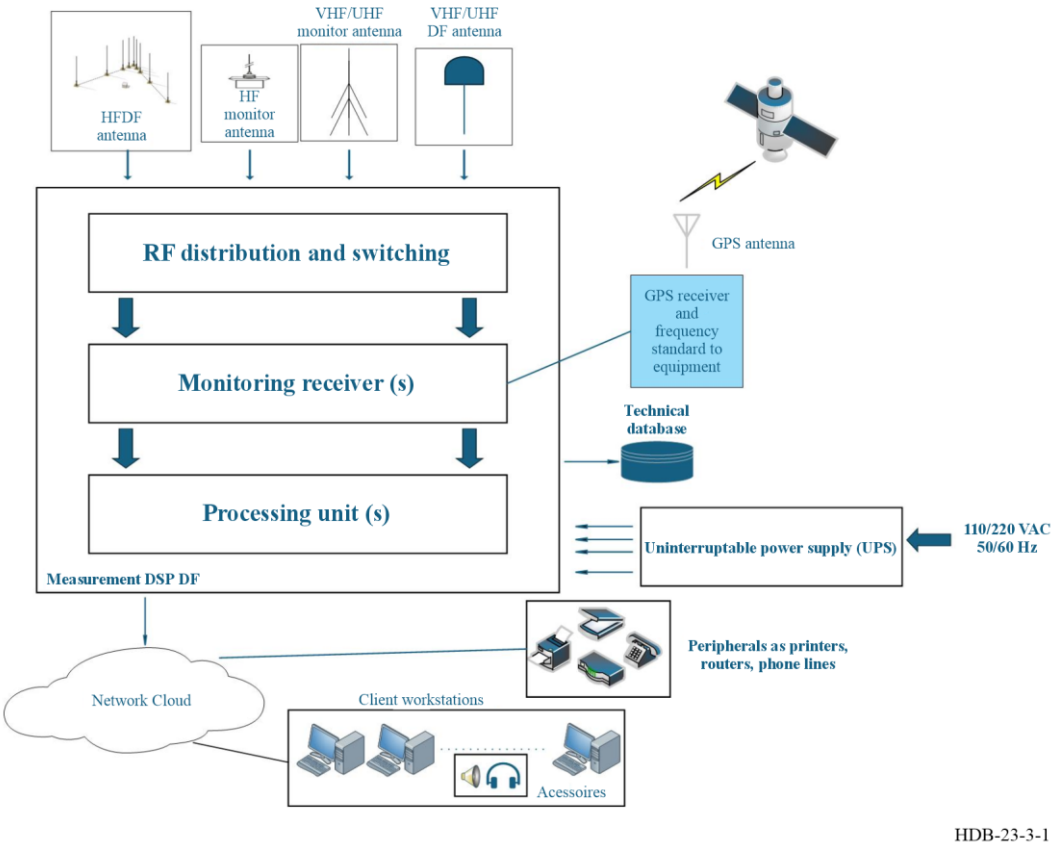
A block diagram of a modern, integrated monitoring station with minimum equipment is shown in Fig. 3-1. The station uses receivers covering frequencies from 9 kHz to 6 000 MHz or higher to provide basic measurement functionality for frequency, field strength, modulation analysis and DF. The control unit allows measurements such as spectrum occupancy to be made over time. In many cases with DSP based spectrum monitoring systems, the RF distribution, receiver(s), and processing units are integrated into a single unit.

A database containing licensing and technical information or a direct interface to a spectrum management system database is provided. This database includes technical information on licensed stations and their parameters, which allows an integrated station to identify frequencies on which there are transmitters that are not included in the database and therefore are presumably unlicensed, and to identify transmitters that are not operating within their licensed parameters.

It should be noted that the overall accuracy of radio monitoring systems depends on more than just the specifications of individual components such as receivers and antennas. Relevant parameters such as linearity, sensitivity, azimuth accuracy and field strength accuracy may also be influenced by the type and length of the cables between the system components and by environmental conditions.

FIGURE 3-1

Block diagram of an integrated monitoring station



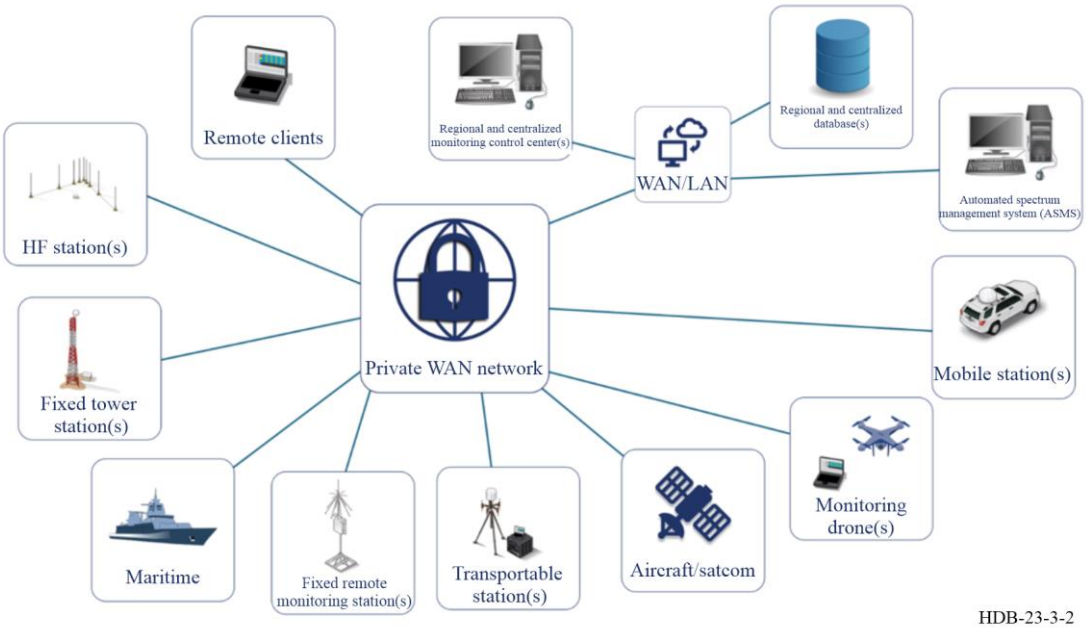
The design and placement of each monitoring station depend on a number of factors that are discussed in detail in Annex 1 to the Handbook, Monitoring System Planning and Tenders. The goal of the regulatory authorities is to have the necessary infrastructure to allow for continual effective management of the wireless spectrum and conduct all the necessary tasks. Deploying this infrastructure involves a variety of trade-offs including budget considerations for the level of national coverage, types of stations, topography and population/communications density.

3.1.2 Station equipment networks

Modern digital signal processing (DSP) techniques allow for varying types of equipment deployed into an interconnected network of stations. The DSP technology combines functionality specifically designed for spectrum monitoring into single packages. These stations may include fixed tower, and rooftop type deployments, mobile deployments and transportable stations and monitoring drones. Different stations may exist for monitoring VHF/UHF/SHF and HF or HF DF arrays. Further, many of the fixed and rooftop deployments make use of all outdoor receivers and processing equipment in order to reduce the infrastructure and the stations footprint at these locations. A simplified network architecture is shown in in Fig. 3-2 and more detailed information about this topic can be found in Chapter 4.

FIGURE 3-2

Spectrum monitoring network architecture



The spectrum monitoring architecture supports a variety of stations including that provide varying degrees of functionality including basic monitoring and geolocation capabilities. The stations are designed to each deployment and maximize monitoring coverage. The overall network of stations is interconnected typically within a private Wide Area Network (WAN) such that an operator can access any station within the network. Further, the monitoring network is interconnected with regional and national databases including the Automated Spectrum Management System (ASMS).

The types of station equipment depend on the frequency range, coverage and station type – fixed, mobile, or transportable. Each of the configurations offer advantages based on their type of deployment even though some performance capabilities may vary.

3.2 Types of monitoring station

The following types of monitoring station are defined:

– fixed monitoring stations;

– mobile monitoring stations;

– transportable monitoring stations.

Stations are categorized into these different types because each type has a different purpose to the regulator and may have different specifications for the antennas and/or receivers.

3.2.1 Fixed monitoring stations

Fixed monitoring stations are the central element of a monitoring system. In their coverage area they generally allow all measurements to be carried out, without limitations such as insufficient working space, inadequate possibilities to set up antennas and limited power supply.

There are two approaches for determining the location of a fixed monitoring station. It can be established either at a place where a minimum of interference from man-made noise and radio emissions is expected, or in highly populated regions where many emissions, including low-power emissions, can be received. The first approach is particularly suitable for HF monitoring stations because they are very sensitive to interference, and propagation conditions allow them to be located far from transmitter sites. For VHF/UHF monitoring stations the second option will be chosen as the propagation conditions do not permit such stations to be located far from transmitters. However, great care should be taken not to overload the receivers by strong signals,

e.g. from broadcasting transmitters, and create intermodulation products (see Recommendation ITU-R SM.575). In practice, different requirements will make it necessary to find a compromise.

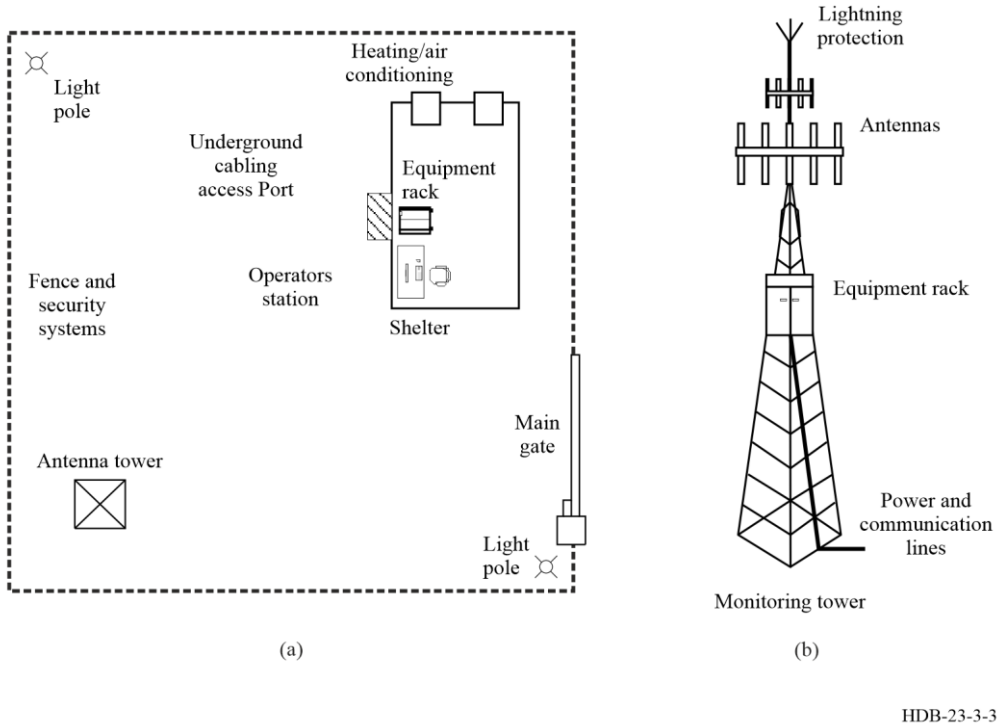
Details regarding buildings and property are contained in § 2.5. For the special requirements of satellite monitoring stations see § 6.1 and Report ITU-R SM.2424.

The main drawback of fixed, manned monitoring stations is the very fact that they are fixed and that, for financial reasons, they cannot be established in sufficient numbers. Therefore, such stations are frequently complemented by remote controlled monitoring stations, which may be equipped with measuring receivers and/or direction finders, depending on their purpose. Advanced equipment not only allows stations to be operated remotely, but also allows measurement programmes to be carried out automatically, with results being transmitted to the manned monitoring station at a later time, and initiates an alarm when certain limits are exceeded. A more detailed description of the remote control of equipment and automation of monitoring is given in § 3.7.

Figure 3-3 presents sketches of configuration for remote fixed stations, either with a larger container space that allows temporary local operation or without this space, allowing only remote-controlled operation.

FIGURE 3-3

Fixed monitoring stations diagrams
(a) Larger site with shelter for local operation; (b) Smaller site with all equipment attached to the tower



Furthermore, in some situations it might be difficult for administrations to find appropriate sites to install fixed stations, and solutions allowing minimum infrastructure work may be necessary.

For example, solutions allowing simple installation of a fixed station on the top of a private building, with very few infrastructures works and minimum nuisance to inhabitants, could be requested by administrations. Such fixed stations have the following main characteristics:

– remote controlled;

– neither a building nor large shelter is required next to the mast;

– reduced power consumption for a whole fixed station.

3.2.1.1 Fixed station VLF, LF, MF, HF

Fixed monitoring stations in the VLF/LF/MF/HF bands are very important for long distance signal analysis and high-power transmitter analysis, including monitoring near borders or in large countries, DF, and single station location (SSL), where a single station can measure elevation and azimuth angle and use ionospheric information to locate a transmitter.

For these frequency bands, the wavelength is very long such that the monitoring station design is most influenced by the desired functionality and size of the antenna. Generally, the fixed stations in this frequency range will be using higher performance antennas, that will need more land area.

One long-range, wide-aperture DF array may be from 50 to 300 m in size and provide directional bearings. Antennas could be either omnidirectional or directional. Other similar monitoring stations can provide additional bearings to enable determination of the transmitter location by triangulation. (Frequency range from several 100 kHz up to about 30 MHz.)

3.2.1.2 Fixed station VHF/UHF

A primary benefit of a fixed monitoring station is the ability to elevate the antenna to the apex of a high fixed mast, thereby enhancing line-of-sight (LoS) for distant transmitters. When deploying such antennas in urban environments, it is crucial to mitigate multipath effects caused by building reflections. Traditionally, equipment has been installed in manned or remote shelters with extensive cable runs to the mast's summit. However, advancements in technology now allow for the integration of receiver and processing capabilities into a single unit. Consequently, many remote stations are now directly installed on towers and rooftops, significantly reducing installation and maintenance efforts. Some configurations may expose the equipment to environmental conditions, as illustrated in Fig. 3-4.

FIGURE 3-4

Typical modern integrated radio spectrum monitoring station

HDB-23-3-4

Omnidirectional DF antennas are advantageous for general monitoring at fixed stations and for covering extensive areas, particularly for automated tasks. Larger omnidirectional antennas are necessary to enhance sensitivity in the lower VHF band. Sensitivity can be marginally improved by employing a rotating high-gain log-periodic antenna system with cross-polarization (both vertical and horizontal) for the required frequency ranges. Increasing the height of an omnidirectional antenna is generally more cost-effective due to the LoS nature of VHF/UHF propagation. Additionally, fixed stations in the VHF/UHF bands can be equipped with active HF antennas to enable HF monitoring coverage.

For VHF and UHF band, rotating receiving antenna can be an option either in manned or in remote controlled monitoring stations. In order to reduce the side lobes, the Dolph-Tchebyscheff optimum distribution antenna pattern is required. An example of rotating antenna in VHF/UHF band is shown in Fig. 3-5.

FIGURE 3-5

Example of rotating antenna in VHF/UHF band

HDB-23-3-5

For frequency bands above 3 000 MHz, a large number of sensors may be required for fixed stations, resulting in increased costs for the competent authority. Therefore, equipment selection should be made in accordance with the specific circumstances and operational requirements of each administration.

3.2.1.3 Compact Monitoring Stations VHF/UHF/SHF

Fixed stations are typically installed on high towers or tall buildings to maximize LoS advantages and enhance coverage. Digital Signal Processing (DSP) technology enables the deployment of much smaller stations that retain many of the capabilities of traditional fixed stations, providing comprehensive ITU monitoring solutions. These compact stations are particularly effective for monitoring in remote areas and challenging topographies, such as mountains, valleys and remote islands.

FIGURE 3-6

Compact station

HDB-23-3-6

3.2.2 Mobile monitoring stations

Mobile monitoring stations have the function to carry out all those monitoring operations where the low power of the transmitters, the high directivity of the antennas and the particular propagation characteristics make it impossible for measurements to be made by fixed stations

A mobile monitoring station provides the same functionalities as a fixed station but is housed in a vehicle that can be relocated as needed. This setup allows for flexible deployment of measurement resources to address specific complaints or monitoring requirements and can be positioned along the LoS propagation path of a signal of interest. These stations are particularly effective for cellular network monitoring, where the small cell size makes mobile monitoring advantageous, and the received signal levels do not necessitate high-sensitivity antennas. Mobile monitoring stations can work in tandem with fixed stations; for instance, if a fixed station detects a signal with a low signal-to-noise ratio (*S*/*N*), the mobile station can achieve better results by moving closer to the transmitter. They are also essential for monitoring in areas where fixed stations cannot be deployed. Given the LoS nature of UHF band propagation, fixed station coverage is often impractical. Example mobile vehicles equipped with omnidirectional DF antennas are depicted in Fig. 3-7.

FIGURE 3-7

Examples of mobile monitoring stations

HDB-23-3-7

This section deals with the special aspects of monitoring tasks due to the mobile monitoring stations only. The considerations being common to all siting, measuring, networking, data handling, etc., problems can be found in the appropriate Chapters.

The design of mobile monitoring stations varies considerably according to their purpose, scope and operating conditions. The complexity of the equipment and its proper operation together with the problems of weight and power consumption usually necessitate a specially equipped vehicle capable of rapid movement. Some systems among mobile monitoring stations are penetrating the vehicle (therefore ‘specially equipped’), while there exist also non-penetrating mobile monitoring systems (without modifications) which can be set up on any vehicle and removed from it (e.g. by magnet mounting) in short time. In some cases, the mobile unit may carry additional portable equipment for making specialized measurements in locations that are not readily

accessible by the vehicle. Such equipment may in some cases serve as both portable equipment or vehicle equipment, depending on form factor and required measurement capabilities.

In the VHF/UHF/SHF frequency ranges, some configurations resemble those of fixed sites in terms of antenna and processing equipment. Mobile stations are further categorized based on the type of vehicle and configuration, such as smaller SUVs or vans as detailed in § 3.2.2.2. Antennas can vary in size, with options available to minimize space usage on smaller vehicles or to be mounted on an erectable mast for increased height when stationary.

Mobile monitoring stations offer the flexibility to monitor SHF frequencies, including microwave transmissions. Directional antennas on these stations can rotate to locate and monitor signals within the SHF band, where transmissions often use directional antennas with narrow beamwidths. These transmissions are more challenging to detect, requiring the monitoring antenna to be within the transmission beam. This setup allows for the interception and analysis of microwave links, whether direct path or secondary lobes of emission antennas. In remote areas, higher directional gain can improve signal-to-noise ratio (*S*/*N*) and enhance reception of distant signals.

Antenna size is the primary limitation for VLF/LF/MF/HF mobile monitoring stations. Mobile stations equipped with active antennas can monitor and direction-find (DF) close ground wave signals. These signals may originate from unauthorized HF users or potential interference sources affecting other communication bands. When such signals are detected, the mobile station can be driven closer to the transmitter to increase the *S*/*N* and pinpoint its location.

Mobile monitoring stations mainly cover frequency range 20 MHz – 6 GHz which may be extended up to 40 GHz or more. There are a variety of types of mobile monitoring stations, including vehicle-mounted stations, manned airborne monitoring stations, maritime monitoring stations, satellite monitoring stations, and commercial drone monitoring stations, all of which are discussed in the following subsections. The word "platforms", where the equipment is installed, is used in this Handbook to describe the various types of mobile monitoring stations, to distinguish them from the three types of stations, fixed, mobile and transportable.

3.2.2.1 Navigation and positioning systems

Contrary to fixed monitoring stations, whose position remains unchanged, all mobile monitoring stations should be equipped with a positioning/navigation system so that their exact location can be determined anytime and anywhere. This will ensure the location of the test system can be identified at the moment data is recorded. Moreover, if the mobile monitoring station is equipped with directional antennas and/or direction finders, it is also necessary to know the orientation (bearing) of the vehicle.

The accuracy required of the positioning information varies depending upon the goals of the measurement and the type of system being measured. For example, accuracy within 100 m may be sufficient for performing the coverage contours of a TV or radio broadcasting station. Accuracy within several meters may be required when mapping the signal coverage and quality of a "micro-cell" system.

Navigation systems require no interaction from the operator and can be used in vehicles, on ships and on aircraft. Account should, however, be taken of the fact that these systems rely on the satellite's visibility and hence cannot determine the position of a vehicle in, for example, a tunnel.

To overcome loss of satellite navigation signals, systems are commercially available, which use a gyrocompass and a rotational transducer coupled to a vehicle's drive train to derive vehicle position. A combination of different systems may be appropriate.

All positioning systems on board should be equipped with a communication interface so that the positioning data can be stored together with the measured data in a process controller, e.g. field-strength values paired with coordinates and time.

Details regarding the different navigation and positioning systems are given in § 7.1.

3.2.2.2 Land vehicles monitoring platforms

3.2.2.2.1 General considerations

Before a vehicle is selected, the area of operation and the monitoring tasks to be performed should be well identified to optimize the choice.

Based on the area of operation (urban, suburban, rural, mountain) the most appropriate vehicle (passenger cars, van, 4 × 4 vehicle…) should be selected. The monitoring tasks to be performed define the measuring equipment to install and facilities to fit out in the vehicle.

Possible choices could be:

– dedicated vehicle for specific radiocommunication measurements (FM broadcasting measurement, IMT coverage area, Quality of service measurement);

– dedicated vehicle for specific frequency band measurements;

– vehicle for general purpose;

– not dedicated vehicle with basic equipment;

– dedicated vehicle for security use.

The advantage of a general-purpose vehicle for all kinds of measurement task is that it can be employed for a variety of functions. There will always be special measurements, however, which cannot be carried out using a general-purpose vehicle. Measuring equipment that has been mounted in racks can be easily adapted to the requirements of a given task, provided there is sufficient space. The main disadvantage of a general-purpose vehicle is its large size, required to accommodate all the necessary apparatus and antennas, and the resulting difficulty in manoeuvring the vehicle in cities and off-road.

Specialized vehicles offer the benefit of being equipped with apparatus perfectly suitable for the measurement task to be performed, and of frequently being smaller than other vehicles. As they can only be used for special functions, however, they will often be parked idly in the garage.

The use of not dedicated vehicle is becoming more common as the equipment have reduced requirements in terms of power and space requirements. The choice of a not dedicated vehicle may also be dictated by the need to not make the vehicle easily recognizable when used to locate an unauthorized transmission, since in some cases such operations can last several days.

If a vehicle is to be used for missions that last several days, it should be considered where the staff will sleep and wash. Where hotel accommodation is not provided, the vehicle will have to meet additional requirements, which will considerably influence its size and price.

A vehicle's crew generally consists of two persons: an operator and a driver/assistant who may have only basic knowledge of radio engineering. If only one person were on the vehicle, that person would have to drive the car and simultaneously handle the measuring equipment, a combination that should be avoided for safety reasons. Moreover, it has proved useful to have a second person as a witness. It may even occur that three people are on board, for instance when a new colleague is trained. This does not result in additional requirements, however, as most vehicle types have at least three seats.

3.2.2.2.2 Antennas for mobile monitoring stations

For monitoring antennas and their characteristics, please refer to § 3.3. This section only describes the limitations and auxiliary attachments taking into account characteristics specific to antennas for mobile monitoring stations.

The types of antenna used in mobile monitoring vehicles will vary according to the frequency and the nature of the measurements carried out. They should also be adapted to the traffic conditions and the installation requirements.

The limitation on the antennas of a mobile monitoring station concerns the size and the number. Owing to the inevitable lack of space, the antennas will have to be small unless, as is sometimes the case, collapsible antennas are used which can be set up on the ground near to where the vehicle is stationed.

It should be taken into consideration during the measurements that the vehicle itself has a distorting effect on the characteristics of the antenna. A "clean" (unmodified) antenna pattern can only be obtained at a sufficient distance from the vehicle, or at a sufficient height above the roof when the antenna mast is extended. The problem concerns the polarization as well.

Omnidirectional antennas can be used and are particularly suitable for general scanning of the spectrum. Directional antennas can be used in order to improve the directivity, the signal/noise ratio or to increase gain and thereby to reduce interference in field-strength measurements, as well as for direction-finding activities.

A wide variety of directional and direction-finding antennas are available from HF up to the GHz frequency range capable of meeting all the requirements of a mobile monitoring station.

As antennas for frequencies above 1 GHz have a small aperture, which may be in the order of down to 1 degree only, depending on the frequency, hydraulic supports may be needed for the measuring vehicle unless a separate tripod is used.

Directional antennas permitting a rough determination of the direction should be distinguished from the special direction-finding antennas available for the various frequency ranges.

The directional antennas however should be arranged to be easily steerable from the inside of the vehicle towards the direction of reception either by hand or by electric motor. The operator should be able to check the orientation of the antenna easily. For automatic measurements the position information should be available for remote control. A rotor, which can be controlled by the process controller, is recommended.

It should be possible to raise the antenna to a certain height above the roof to improve the sensitivity, reduce the influence of the vehicle upon the measurements and raise the antenna above any obstacles to wave propagation. This applies particularly to antennas intended for VHF and UHF reception. The height to which antennas can be raised should be 10 m at least.

For this purpose, special telescopic masts are used, consisting of a series of closely fitting steel tubes, which are driven upwards by a pneumatic or hydraulic system. Other widespread solutions use a wire-rope system driven manually or by an electromotor. When choosing the system, the weight of the antenna should be taken into consideration along with the measurement method to be used (stationary-site measurement with the mast extended during a long period or measuring from point to point and extending the mast again and again). The mechanical construction of the antenna supports (masts) fixed into or onto the vehicle has an important role because of the heavy stress they generally bear.

The instantaneous antenna height should be readable from inside the vehicle. To simplify height-dependent field-strength measurements, a mast steered by a process controller is recommended with the instantaneous antenna height being available at the processor.

Proper precautions should be taken when hoisting a mast of this height, and allowance should be made for the weight of the mounted antenna or wind pressure, which might cause dangerous swaying of the support and so threaten its stability. When raising the mast, care should be taken to see that there are no overhead electric wires in the vicinity.

To prevent the occurrence of an electromagnetic field around the mast, it is preferable to paint the mast with a signal absorber and an inhibitor of reflection and refraction.

Apart from antennas for use on open ground, which can be dismantled, the antennas of a mobile monitoring unit are normally mounted on the roof of the vehicle, which should therefore be easily accessible by means of a small outside ladder, or better still, from inside the vehicle through a trapdoor in the roof to which easy access can be provided by means of an inside ladder.

To make the antennas easily interchangeable, it is wise to adopt some form of standard fixing system, for example of the bayonet type, which can be used for all the station antennas. The antenna should also have a suitable connector to which the down lead can be connected. A system able to change automatically the polarization can be installed on the top of the mast, avoid extending the mast again and again.

A single length of flexible cable can be used, which hangs down parallel to the mast and is wound up on a reel inside as the mast is lowered.

To avoid complications when making field-strength measurements, it is essential to choose a cable, which has the correct characteristic impedance and is of a low-loss type. The attenuation of each length of cable at the various frequencies should be known and allowed for.

Interference considerations for mobile monitoring: In conducting mobile monitoring, one should consider the radio frequency environment, especially in RF environments where strong signals are present. The strong signals can generate intermodulation distortion within the monitoring or measurement system, making it difficult to make accurate signal measurements in such environments. This may be particularly important with radio direction-finding equipment installed in monitoring vehicles, since those systems often use internal amplifiers and active antennas, which are more susceptible to internally generated intermodulation effects from strong signals.

In these RF environments, there are usually no problems using systems which use passive (non-amplified) antennas. However, monitoring systems which use low noise amplifiers and/or active (preamplified) antennas are much more susceptible to intermodulation. In this situation two approaches can be used separately or together to assure that systems are not impacted by strong signals:

Dual-mode antenna

A dual-mode antenna can switch over from active (amplified) mode to passive (non-amplified) mode. It operates normally as an active antenna, and in areas where strong signals are present, it switches into passive mode, so its operation is not impaired.

Inserting a band rejection filter

Installing a band rejection filter (BRF) for a portion of the frequency band where strong signals are present is another possible solution. The BRF is installed in front of the first signal preamplifier in a signal distribution system and can prevent strong signals from affecting the system. Of course, when a BRF is used, the corresponding frequency band blocked by the filter is not able to be measured. Also, consideration should be given to any effects the filter may have on gain, signal group delay, or other filter characteristics that may affect monitoring or direction-finding systems. To avoid that rejected signal overcome the rejection barrier, well shielded cables and connectors have to be used.

Intermodulation effects are discussed in more detail in § 3.4 on receivers.

3.2.2.2.3 Requirements to be fulfilled by the vehicle

The choice of vehicles for mobile monitoring platforms is governed by a variety of factors. Each individual purchasing authority will prioritise these factors according to their own needs, but as a minimum, the following should be considered before specifying vehicles.

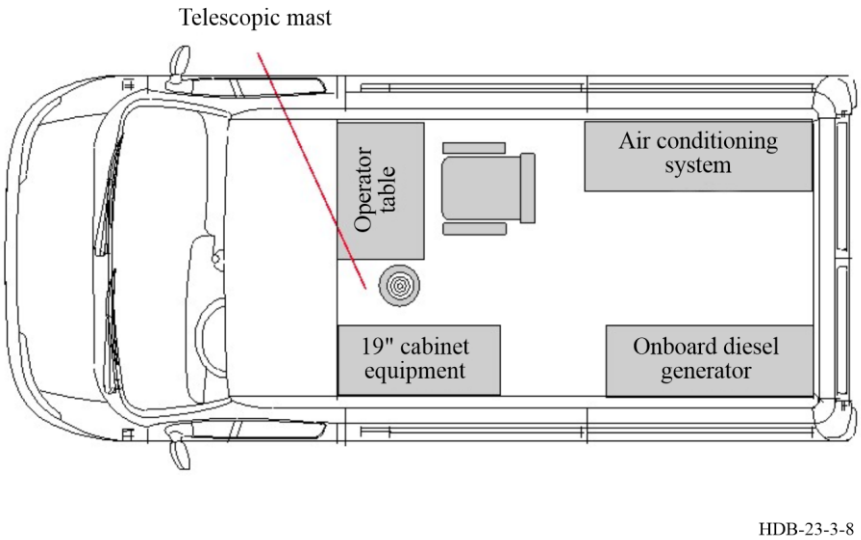
Mobile monitoring platforms can be developed from a variety of commercial vehicles. A production vehicle with standard drive train components will offer the lowest life cycle costs. The availability of spare parts should be part of the vehicle specification. It is advantageous to procure vehicles from manufacturers who have local service facilities already in place. Vehicles intended for use also on unpaved roads and off-road will need four-wheel drive and sufficient road clearance.

There should be sufficient leg-room for both the driver and the operator. During measurements carried out on the move, the operator should sit facing forward. In any case, the vehicle will have to contain everything needed to ensure that the measurements can be carried out easily. The equipment should be arranged in a handy way so that personnel are able to carry out measurements with minimum movement. The operating equipment should be near at hand. The dimensions of larger vehicles should allow the operator to stand upright.

A bus-type structure as shown in Fig. 3-8 without a partition between driver's cabin and operator's room is preferable so that the driver can have direct contact with the operator's room. This also gives operators a view of the direction in which they are moving and gives the driver a chance to go to the operator part without having to get out of the vehicle. For vehicles without a partition between driver and operator's room, the driver seat should be protected against objects that could be thrown during strong braking.

FIGURE 3-8

Interior of a mobile monitoring platform



Windows in the operating area of the vehicle should be included to provide natural lighting for the operators and to give them an all-round view. Curtains or shutters should be provided, however, so outside light can be excluded in those cases where it interferes with viewing of displays such as spectrum analysers, computer monitors or televisions.

Great importance should be attached to safety. Every seat should be equipped with a safety belt, and equipment should be securely fastened so that it cannot shift and cause injury while the vehicle is in motion or in case of a minor collision. If there is a seat for the operator in the rear of the vehicle, it should be possible to lock that seat. The roof of large vehicles should be fitted with a folding safety rail to protect staff from falling.

The interior of the vehicle should be equipped with equipment mountings to secure the electronics and to offer some protection against shock and vibration. Equipment may be mounted in standard 19-inch racks, or by special rails and suitably shaped fasteners. This latter may result in a more flexible solution. Whatever the mounting technique, equipment should be easily removed for repairs. Power and signal leads should be properly dressed behind the equipment to the greatest extent possible, to reduce clutter in the work area and to enhance operator safety. Equipment layout should be studied and planned so that the controls and displays used most frequently by the operators are in the most convenient locations.

The body of the vehicle, regardless of design, should have adequate thermal insulation to ensure both proper conditions for the equipment inside, and comfort to the crew. Good thermal insulation will also typically serve as acoustic insulation. The normal vehicle heater and air conditioner will be satisfactory for the driver's comfort, but larger units should be furnished for the equipment and crew compartments. Propane, petrol, or electrical heaters can provide additional heating capacity. Air conditioning of the vehicle itself and of extra cabins, if necessary, can be powered by the vehicle's electrical system, by external mains input, or by an on-board generator. The vehicle's electrical system can be fitted with solar power supply by positioning film solar panels on the external shelf of the vehicle.

The vehicle should be fitted with sufficient interior lighting so that the operators may work without eye strain. Low-voltage fluorescent lighting can be powered by the vehicle's electrical system. Normal incandescent or fluorescent lighting can be powered by an on-board generator or by external mains power where available.

A vehicle's weight is the most critical factor in vehicle selection. A passenger car (estate) has the advantage of being highly manoeuvrable, able to pass through narrow streets, and allowed on squares and streets that are closed to trucks. The vehicle's maximum load capacity of some 500 kg for staff, measuring equipment and additional power supply systems together with its small interior considerably restricts the range of possibilities for its use. However, vehicles of this type have been successfully employed for searching mobile sources of interference or illegal transmitters. The direction-finding antenna can be disguised as luggage, and antennas of a lower sensitivity can even be completely integrated into the roof so as not to be recognized.

Vehicles with a maximum total weight of 2.8 tonnes, which are still considered passenger cars under the road traffic regulations of many countries and have a load capacity of more than 1 000 kg, offer much more flexibility. They can be easily used as universal vehicles, fitted with measuring equipment, mast and direction finders, and offer space for additional antennas and a portable power generator in the rear part of the vehicle. The interior may be formed into a complete mobile measuring platform but it often suffices to have an occasional version of vehicle in which the instruments are interchangeable. However, the power supply, the computer access (e.g. IEC bus), the position determination system, the measuring antennas with their movable supports, and the appropriate means of communication should be ensured in both cases.

Large trucks will be chosen for long-term, quasi-stationary measurements requiring a powerful built-in generating set, or if it should be possible for the staff to stand upright or to sleep in the vehicle. A truck is also required where dish antennas with very small apertures, which require a solid flat platform, are used; in this case the truck should also have hydraulic supports.

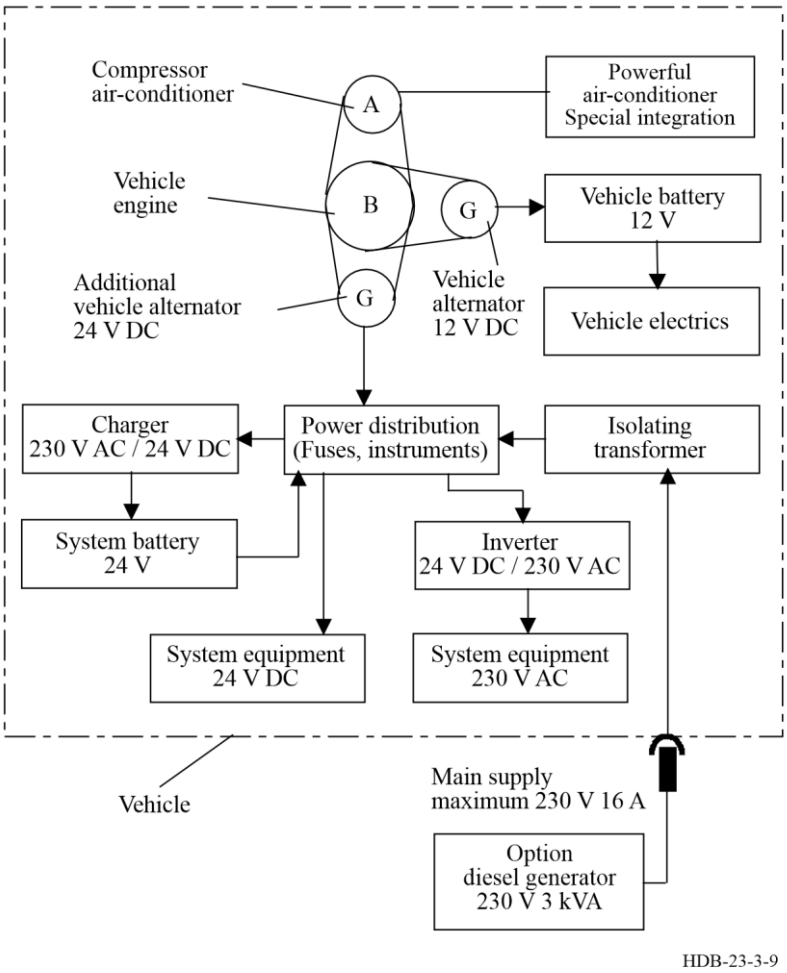
Even in full load conditions, the vehicle should be able to reach a speed of at least 80 km/h on level roads so as not to be an obstacle to traffic. This requires adequate motor power. If the manufacturer offers a reinforced clutch, it should be used, in order to prevent an early failure of this part as a result of the mostly heavy load.

3.2.2.2.4 Power supply

A variety of power sources for equipment in mobile platforms are available. A well-equipped mobile platform will use at least two sources for redundancy. An example is shown in Fig. 3-9.

FIGURE 3-9

Example of a power supply system of a general-purpose vehicle



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The power consumption of modern equipment has eased the mobile unit power problem considerably. As examples, the following typical power consumption figures are for commercially available equipment in the categories cited in Table 3-1. This equipment might be available as separate parts or as a combined system that includes several items, with combined power usually lower than the sum of each part, e.g. a signal processing system consisting of radio frequency distribution, receiver and processor might demand as little as 20 W.

TABLE 3-1

Typical power consumption of spectrum monitoring equipment

Equipment type	Typical power consumption (W)
Spectrum analyser (frequency range up to 8 GHz)	120
Spectrum analyser (frequency range up to 50 GHz)	200
Oscilloscope (bandwidth up to 300 MHz)	60
Oscilloscope (bandwidth up to 6 GHz)	400
Signal generator	150
HF/VHF/UHF monitoring receiver	70
HF/VHF/UHF monitoring receiver with direction-finding functionality	100
Industrial personal computer (PC) with colour display	100

Electronic equipment has also become lighter and more compact. These combined size and power features allow a great deal of capability to be included in a mobile unit, which generates its own power. In many cases, however, equipment should be operated remotely from the vehicle. Such equipment should be capable of battery-powered operation. There are modern test and communications equipment in almost all categories (analysers, oscilloscopes, receivers, signal generators, direction finders, computers, etc.), which can be operated on battery power. Most such equipment can also be operated inside a mobile unit on AC power.

The level of charge of system battery should be monitored, and visual or/and acoustic warning should be provided before the system battery is completely discharged.

Compact gasoline-powered generator sets with up to at least 2 kVA are available which can easily be fitted into the rear compartment of a cargo van. Some electronic news gathering vans include two such generators. Thus, power consumption should no longer be the critical factor in equipment selection for mobile units.

Batteries or secondary cells

Power supply from batteries or rechargeable batteries is the only solution for portable equipment for use in remote places, which are inaccessible to vehicles. This situation often occurs in the case of field-strength measurements.

Alternators coupled to the engine – Inverters

Since most of the electronic equipment employed for measurement purposes is designed for direct supply with AC power from the mains at 115 V/60 Hz or 220-230 V/50 Hz, the vehicle should be equipped with a generator capable of providing an adequate supply of power with these characteristics.

A solution is to use an inverter supplied from a battery in the vehicle. An auxiliary battery of higher capacity may also be used if this is needed to ensure the requisite independence of operation. This, however, raises additional problems of maintenance and periodic recharging.

The high efficiency, operating reliability, silence, high stability of both the frequency and the voltage generated and the absence of electrical interference which can be obtained from a modern inverter system using entirely solid-state elements suggest that these are the most suitable devices to use at least up to the 500 VA limit.

For higher outputs, the size and weight of the batteries required guaranteeing the necessary independence from the mains supply and the inevitable maintenance difficulties involved detract from their utility as power sources for mobile monitoring platforms.

Generating sets

Mobile monitoring platforms generally need a power supply of more than 500 VA. Current is required not only for the electronic equipment, but also for the ancillary equipment: small electric motors, fans, lighting, not to mention radiators, air-conditioning plant, etc. The connected load of a medium-sized mobile monitoring platform can easily reach, and in some cases even exceed, 2.5 kVA. This load may be required for many hours, and sometimes days, of independent operation. Under these conditions, the most convenient solution is a generating set driven by an internal combustion engine.

The drawbacks common to all low-power petrol engines are: noise, tendency to vibrate and, sometimes, to cut out, owing to their operating characteristics and weight distribution problems. Moreover, the ignition system can easily cause electrical interference if not fitted with adequate suppressors. Therefore, diesel engines should be preferred.

The installation of a generating set on the vehicle calls for particular care to prevent its noise reaching the cabin and becoming a nuisance to the operators to the detriment of measurement accuracy. Normally, it is housed in a fully sound-proofed compartment at the side of the bodywork and secured by an elastic suspension system. Access to the set for the purpose of inspection, maintenance and starting is from the outside by means of a flap, which should be very carefully fitted so as to prevent noise leaks.

When the generating set is intended for intermittent use only, for example, to operate the air-conditioning plant from time to time, to recharge the batteries during a long series of measurements, or to cover temporary power peaks, it may be advisable not to install a generating set on the vehicle but to make use of a portable model which can, if necessary, be placed at some distance from the vehicle, with a cable connection so that its operation will cause no serious disturbance.

Mains supply

Even when a mobile monitoring platform can be equipped with an independent power source, it is always preferable to take advantage of direct supply from the mains whenever possible. This should be done in order to keep the auxiliary lighting and air-conditioning plant in good running order, or, of course, to recharge the service batteries and the built-in instrument batteries through their respective charging devices.

Evidently, connection to the mains replaces the vehicle-borne generators since both power sources obviously cannot be used in parallel. The electrical equipment of the vehicle should necessarily be designed in such a way as to make it mechanically impossible to connect both systems at once.

There should be an isolating transformer on board to avoid the inconvenience of having to earth the vehicle and measuring instruments. Any mains outlet should include a suitable automatic switch set for the maximum current needed.

3.2.2.2.5 Example of a vehicle concept

The vehicle concept should be prepared taking account of the above considerations, the volume of tasks and the number of sites; the financial resources available will generally necessitate compromises with regard to the concept's realization.

Although the vehicle requirements of various countries may differ, several examples of vehicles for mobile monitoring platforms are illustrated in Fig. 3-10.

The vehicle types in this Handbook are classified into four types, as described on the following items:

Type 1: These vehicles are passenger cars (or estate wagons) used to carry passengers, equipment and antennas. The antenna array used for DF and monitoring is mounted in an unobtrusive roof-top carrier mounted directly to the luggage rack on the roof of the car. The monitoring and DF equipment is mounted in the luggage area at the rear of the car, and the operator can be seated anywhere in the passenger area of the car and control the equipment from his laptop. This type of platform can operate while in motion or stationary. The measurement results are stored on the hard drive or flash memory of the laptop and can be downloaded to the fixed station database when the car returns to its home station at the end of the measurement session. Alternatively, with a communications connection the data can be transferred directly to the central station. Typically the monitoring platform can be operated locally, but it can also be remotely controlled by the central station.

A printer can also be provided inside the car. Almost any passenger car or estate wagon can be used as a Type 1 vehicle, especially if it is factory equipped with a roof rack. Because they look like ordinary passenger cars and do not attract attention, these types of mobile platforms are especially useful when searching for illegal transmitters.

Type 2: These are heavy duty 4 x 4 utility vehicles to be used on difficult road conditions where neither Type 1 nor Type 3 vehicles can go (desert areas, mountains, etc.). They contain equipment capable of both monitoring and direction finding while in motion or stationary. These vehicles are equipped with a telescopic mast compatible with the difficult road conditions the vehicle is used for and the compactness of the equipment compartment. A typical mast can then extend the antenna used for monitoring and DF up to approximately 6 m above ground level. The operator can be seated anywhere in the passenger area of the vehicle and can control the equipment from a laptop. With the mast down, this type of platform can operate while in motion or stationary. During normal operation, the electrical power is provided by the high current alternator mounted on the engine of the vehicle, and environmental control is provided by the on-board vehicle air conditioner and heater. There is generally not enough room for permanently mounting an auxiliary electrical generator inside the vehicle. However, these types of vehicles can be equipped with an external generator mounted on a special purpose platform at the rear of the vehicle. This vehicle type is the standard vehicle for rural and mountain area operations where access would be difficult for passenger cars or large vans.

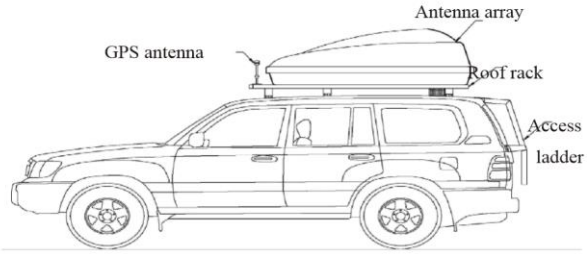
Type 2*bis*: These are similar to Type 2 vehicles, where a mobile monitoring platform is integrated in a shelter installed on a pickup truck. Some operations require both access to rural or mountain areas and unobtrusive appearance without visible antennas for the search of illegal transmitters. For such operations, the entire monitoring equipment can be integrated in a shelter including monitoring and direction-finding antennas, and this shelter can be installed on a heavy duty four-wheel-drive utility vehicle. Naturally, the shelter is made from non-conductive material such as plastic. The antennas can be installed on extendable masts for quasi-stationary operations requiring wider coverage.

Type 3: These are heavy-duty utility vans. They are intended for universal use and are therefore equipped with the same type of monitoring and direction-finding equipment as the Type 2 vehicles, including a mast which can be raised up to approximately 10 m above ground level. An optional mast can be added to raise additional monitoring antennas if needed. When the mast is not raised, the Type 3 vehicles can operate while in motion as a homing platform. In addition, the auxiliary generator is built into the vehicle and properly shielded for noise and electromagnetic interference. Type 3 vehicles use AC power, either from the on-board generator or from the mains when vehicle is stationary. This vehicle can easily accommodate one passenger in the front and two or three operators in the back. This vehicle type is the standard vehicle of the monitoring service, primarily used for investigating interference. It may also accommodate transportable/portable equipment to perform monitoring and direction-finding tasks equipment to be used outside the vehicle to reach an area inaccessible to vehicles.

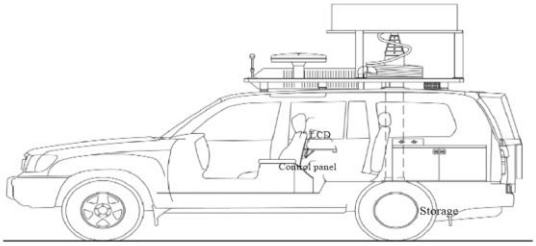
Type 4: These are a particular kind of utility vans. They are intended for stationary activity to be provided for example during major events, (see Report ITU-R SM.2257) or for the analysis of vertical distribution of the field strength. They are equipped with two masts, one able to reach 23 m and one secondary which can be elevated up to 8 m. The useful range of measurement is from 4 m to 23 m. The vehicle is built without a partition between driver's cabin and operator's room. The available space is divided in three areas. On the rear is placed the main mast which is centred on a nylon sphere around which it can develop a precession movement. Up to a height of 10 m, it is equipped with an automatic verticalization function working up to 5 degrees of inclination. Above this height it is necessary to use hydraulic supports to stabilize the vehicle. Above 10 m the mast can be elevated if it adjusted to be raised in vertical position. The cable is organized in spiral elevating along the mast. In the central part of the vehicle is placed the meeting room which can host up to six persons around the central table. On the separation panel, which isolates the mast area from the rest of the vehicle, is placed an LCD flat display. In the last sector of the vehicles is available the instruments area where up two personnel can work. In such area is available the control panel of the mast, whose elevation can be controlled by camera or directly by a trapdoor. A secondary mast is placed just behind the instruments area which can be managed for its rotation manually. All types of electrical supply are available (system battery, main supply, solar panels).

FIGURE 3-10

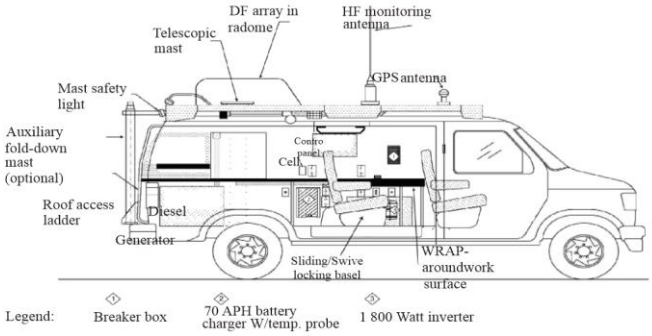
Examples of mobile monitoring platforms



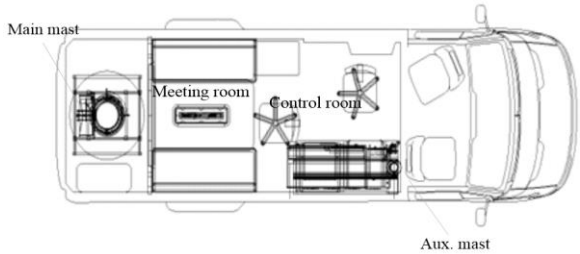
Type 1



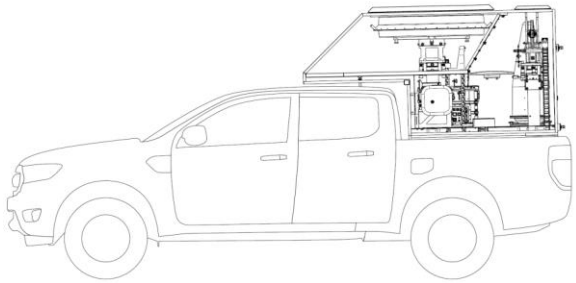
Type 2



Type 3



Type 4



Type *2bis*

HDB-23-3-10

Other vehicle types, of course, may be used. Examples include trucks, equipped with a shelter that provides space for more monitoring positions.

For the sake of completeness, the vehicles of the radio inspection service should also be mentioned here. This service might use Type 2 vehicles equipped with a mast but not direction finders. These vehicles are mostly used for investigating interference to broadcasting transmissions and for inspecting radio installations. For this reason, they have special television broadcasting antennas, but they also cover the whole frequency range up to 18 GHz. Portable equipment for the inspection of radio installations is also available.

3.2.2.3 Commercial drone monitoring platforms

The application of commercial drones in this Handbook is understood to be conducted within visible line of sight by ground operations and is for use within the country of the authorities operating the drone.

Commercial drones are increasingly deployed as possible mobile monitoring systems delivering broad LoS coverage and flexibility as both mobility and height restrictions are removed. They mitigate several of the disadvantages of aircraft-based monitoring platforms, and their more flexible operation and significantly reduced costs make them an attractive alternative for many spectrum monitoring tasks. Obtaining a drone is a much more economic approach than repeatedly renting an airplane or helicopter. A drone requires less space to operate in, and flight permission is easier to obtain. Once the payload is connected, the drone can immediately take off. Thus, deployment is much faster and operation more flexible.

A commercial drone monitoring platform usually consists of a drone equipped with the antennas and equipment and a ground station that could remotely control the drones and display the monitoring data. Commercial drones-based spectrum monitoring enables large-area coverage at reduced cost, with simpler deployment and greater operational flexibility than conventional aerial systems.

They are particularly useful in providing a broad area snapshot of spectrum activity and can also be used to fly between microwave transmissions in order to identify interference issues within the SHF band.

A drone monitoring platform can be well suited to monitor technical parameters like power, bandwidth, polarization, radiation pattern to detect non license compliant operations. Moreover, commercial drones could perform special actions such as hovering and circling. This greatly expands its application scenarios, such as: monitoring in the locations where the airborne monitoring platforms cannot easily approach, mapping the three-dimensional antenna patterns of radio transmission systems and evaluating the quality of satellite uplink signals.

A drone represents a valuable solution to detect and identify unknown or interfering signals in scenarios where the transmitters cannot be easily reached by vehicles or airborne, as on top of mountains or high buildings. The system could operate in interactive as well as in autonomous mode. In interactive mode, a monitoring expert has live access to the system. The route and tasks can be configured and controlled with results displayed in real time. In autonomous operation, the tasks and the route are programmed via software before the flight; the drone flies the defined pattern and measurements are performed automatically. Multiple payloads can be used with different types of antennas, covering a wide range of frequencies up to 40 GHz or more.

Another area of operation is interference hunting. Interfering signals in the EHF range are very difficult to detect and locate from the ground. Weak interferers in the V/UHF range can be found much faster with a drone-based monitoring system. Flying a systematic pattern along the front of a big building is a much more efficient way to locate interferers and illegal transmitters than walking through the house with portable equipment.

Communications between drone and ground stations typically use ISM bands (2.4 GHz and 5.8 GHz) which can be subject to interference. For that reason, it is important to have adaptive communication controls to, for example, switch frequency channels in the case of interference.

Despite the advantages listed above some limitations should be noted in the use of commercial drones:

– Weather conditions dependency: drones operativity can suffer of wind, high or low temperatures as well as high humidity.

– GNSS connectivity dependency; drones without a reliable GNSS signal are difficult to operate.

– Weight and size limits imposed on the monitoring equipment (antennas, receivers, power supply) installed on board. The weight of the payload may vary on the type of drone used, but typically should not exceed 10 kg in order to keep the total drone weight below 25 kg, to be within the more flexible open category operational limits.

– Short operating time: due to the power supply limitations the flight duration of commercial drones is usually limited to a few tens of minutes.

– National flight regulations: national regulations can limit flight regions, time of day or flight controls for each type of drone (including total weight and size).

– Measurement uncertainty: drones try to keep a target position using various sensors but several factors (e.g. weather conditions or wind) can introduce volatility or sudden movement during the signal acquisition time, resulting in measurement uncertainty and variation of the results.

It is important to highlight that some of these limitations are constantly being challenged by the technological advancements in the efficiency of various drone components, especially batteries, engines and the monitoring equipment that compose the payload.

Alternatives such as the use of tethered systems may allow the extended use of the drone, although restricting its movement. In practice, such mode of operation is an efficient alternative to replace masts in mobile units, enabling the use of monitoring antennas up to more than a hundred meters in height from the ground, without any fixed installation.

Details on the use of commercial drones for spectrum monitoring are provided in Report ITU-R SM.2486.

3.2.2.4 Manned airborne-based monitoring platforms

The use of manned airborne as mobile monitoring stations instead of land mobile monitoring platforms allows accomplishment of the monitoring tasks with some advantages as well as disadvantages, as shown in Table 3-2.

3.2.2.4.1 Operations of airborne monitoring platforms

General purpose procedures

Flight missions should be duly scheduled and well planned. This implies that some coordinating activities should take place following the general guidelines listed below.

a) Request for flight mission, indicating duration

Monthly or weekly schedules can be fixed only when the activities to be performed and the relative task-time are known, together with aircraft and crew's availability. The term "aircraft" here comprises aeroplanes, helicopters, airships, etc.

TABLE 3-2

Advantages and disadvantages of airborne radio monitoring platforms

Advantages of air mobile monitoring	Disadvantages of air mobile monitoring
1. Quick exploration of broad geographical areas. 2. Opportunity to obtain geographic direction using one platform by obtaining several lines of bearing from different locations. 3. Better opportunity to perform measurements due to line of sight. 4. Rapid location of emergency beacons, interferers and Earth stations which sometimes cannot be detected from ground. 5. All means of measurement of aeronautical flight aid transmissions.	1. Cost of flight. 2. Limitations in weight, power, size, cooling. 3. Limited by weather, winds. 4. Limited flight time due to fuel or electricity limitations. 5. Requires accurate azimuth and depression angle, fast DF capability and antenna tracking. 6. Frequency compensation for relative velocity may be needed.

b) Flight activities coordination

Aeronautical authorities responsible for air spaces where radio monitoring should take place, together with those in charge of aircraft and crew logistic support, should be notified in advance. Flight procedures required for monitoring may in fact require some special coordination, especially in heavy air-traffic areas. Similarly, ground fixed and mobile radio monitoring platforms should also be taken into account during joint coordinated activities.

c) Pre-flight activities

In addition to operational planning and preparation of flight mission (flight plan, aircraft checkout, fuelling, etc.) data obtained from measurements made in previous missions, or available from other sources, should be carefully examined in order to select the functions and the automatic procedures of the monitoring equipment to be used during the flight.

Operational procedures

Monitoring flight mission implies different operational procedures depending upon the requested activities to perform. Such procedures should be carefully planned before each mission.

For instance, it is likely that during monitoring missions, the aircraft will have to fly on predetermined paths, such as loops, at suitable speed and altitude.

Mission altitude can determine the area to be monitored, while speed influences the accuracy of the direction-finding measurements. Moreover, as regards detection of mobile interfering radio signal sources, it could be necessary to perform position by homing the source at low altitudes and speeds.

3.2.2.4.2 Applications – Examples

Mobile measuring systems installed on board an aircraft, an airship or a helicopter is well suited to plot the radiation pattern of antenna towers in both the horizontal and vertical planes. It may also be necessary in a few cases to use a helicopter or an airship fitted with measuring equipment suitable for locating sources of interference that cannot be identified by ground monitoring facilities as earth stations or leakage from cable TV, for analysing phenomena that may result from closely spaced high-power VHF transmitters and for measuring antenna radiation patterns.

In some situations in large cities where mobile ground facilities are “obscured” by obstacles such as high-rise buildings which mask the source of the signal or produce numerous reflections, a properly equipped helicopter or airship provides a high-level of precision in positioning and/or organising the movements of facilities on the ground.

It should be ensured that:

– the height and the distance (or the navigation data, as appropriate) can be registered;

– the antennas are fixed in a reliable way;

– the measuring instruments are installed suitably;

– the necessary data can be collected;

– the instruments are supplied with power during the flight.

Applications for broadcasting monitoring using aircrafts can be found in Report ITU-R SM.2056.

3.2.2.4.3 Aircraft operational requirements

Taking into consideration the general needs of spectrum monitoring activities and measurements to be performed the operational requirements of an aircraft housing an airborne monitoring system should be as follows:

– flight capability for all weather operations;

– manoeuvrability and good stability at low speed/altitude;

– adequate load capacity in order to accommodate all necessary equipment and monitoring staff.

3.2.2.4.4 Aircraft technical requirements

Technical characteristics required for an aircraft housing an airborne monitoring system should satisfy the following criteria:

– autopilot facilities should permit surveillance operations by pre-planned procedures (e.g. grid or circular patterns);

– avionics navigation equipment on board should allow full instrument flight operations; an independent instantaneous aircraft position and altitude computation system should be interconnected to the monitoring processing unit;

– range should be possible to operate for at least two hours in the area under observation in full load conditions, considering altitude levels even below 6 000 ft (1 800 m);

– speed range large enough to allow both quick transfers and homing procedures at low altitudes.

3.2.2.4.5 Antennas

For practical airborne applications, the antenna array considerations dominate the engineering effort and the cost integrating the DF system into the aircraft. These issues begin with determining antenna locations that are physically compatible with the airframe, engineering the antenna hardpoints into the aircrafts to carry the mechanical loads generated by the antennas, impact of the antennas upon the flight characteristics of the aircraft, airworthiness certification of the aircraft, and peripheral issues such as antenna de-icing requirements. As a result, simplification of the antenna array yields significant reduction in the complexity of the system integration.

a) Passive airborne antenna systems

High-performance airborne DF systems using passive antenna arrays have been integrated with aircraft that range in size and capabilities that span the full range of aircraft used in multi-mission roles. The scimitar shape for the VHF antennas adds effective antenna length without increasing the protruding length from the aircraft surface. The system operates principally with signals that are approximately vertically polarized. As a result, the antennas of choice are usually either monopoles or dipoles.

b) Active airborne antenna systems

Active antennas offer extremely wide bandwidth and antenna physical size reduction while maintaining constant sensitivity compared to passive antennas. Active antennas have become practical with the newer generation active devices, primarily field effect transistors (FETs) that permit active impedance transformation while maintaining high circuit dynamic range.

3.2.2.4.6 General requirements for on-board systems

The whole airborne systems set-up should be designed and implemented very carefully in order to ensure maximum safety and reliability of the aircraft. It is important to mention that equipment used in aeroplanes must comply with both ICAO and national regulations.

Some of the parameters, which can directly influence flight operation, are:

– weight and location of equipment on board, so as to avoid any upset of aircraft flight stability;

– structural strength and stiffness of the aircraft after modifications;

– aircraft aerodynamics following installation of the monitoring system antenna;

– thermal and electrical power balance.

The above-listed parameters show the importance of accurate cross-checking, to be performed in order to improve the system reliability and limit operating cost.

Also, simplified maintenance (modular design and built-in test system) and possibility to remove and substitute faulty equipment easily for laboratory checks and calibrations, is the normal procedure in the aeronautical field; that philosophy of maintenance requires adequate availability of spare parts and equipment subsystems.

3.2.2.4.7 Aircraft radio monitoring platform set-up criteria

The main platform subsystems should be based on the following criteria:

a) Automatic position determination system

The aircraft should be able to determine its own position in order to perform signal source position fixing without any special external auxiliary navigation systems beyond existing radio aids. Its navigation system should therefore be self-sufficient.

Moreover, by coupling the navigation system (e.g. inertial and/or satellite system, multi-distance measuring equipment (DME) technique) to the radio-monitoring processing unit, it will be possible to compute the position of radio signal sources for all possible headings of aircraft. However, an independent position and altitude computation system in conjunction with the monitoring processing unit is of advantage.

b) Efficient man-machine interface

Aircraft radio-monitoring operations generally involve limited task-time and minimum personnel on board. Therefore, monitoring equipment should be capable of performing programmable and automatic measuring procedures, reserving manual operations only for very specific tasks.

In any case, data presentation should permit immediate interpretation so that an instinctive cognisance of current aircraft position should be possible for the monitoring staff in flight.

3.2.2.5 Maritime monitoring platforms

The marine environment presents one advantage as well as unique equipment problems that should be considered. The primary advantage to marine mobile monitoring is that the area surrounding the marine vessel is generally very quiet from a radio frequency point of view. Problems include the corrosive atmosphere, multipath due to sea state reflections of radio energy, antenna mounting, and radio frequency ducting over warm bodies of water.

A moist corrosive environment will dramatically shorten the life of electronic devices if not specifically designed for marine use. This usually requires sealed controls, filtered housings and fungus treatment. Alternatively, equipment can be placed in a conditioned environmental location. To prevent moisture build-up a very small amount of heat, often in the form of a small nightlight or leaving the equipment turned on, has a beneficial effect. Left unattended in an unconditioned area electronic equipment not specifically designed for the environment will corrode and develop electrical breakdowns.

Electrical grounding (Earth) is often difficult to achieve on board marine vessels.

Direction-finding equipment should be specially installed and calibrated for the vessel. Mobile, carry on – carry off, gear is not recommended. The direction finder antenna should be placed at a high point on the vessel and, to the extent possible, clear of surrounding obstructions. A particular problem resulting from the antenna being at the top is that nulls occur in the vertical radiation pattern at small elevation angles and wavelengths that correspond to about twice the mast length. Changing the antenna position will improve reception only in part of the frequency range. To solve the problem, it is expedient to mount two antennas at different heights and switch between them as required. The actual calibration should be performed by swinging the ship a full 360°. Satellite navigation and North references are needed to obtain accurate lines of bearing and fixes.

While motion of the vessel can cause problems in instantaneous direction-finding, the effect of pitching and rolling of the vessel can be compensated by determining average line of bearing.

Multipath of radio frequency signals over water is affected by the sea state. While even smooth water will cause multipath difficulties, the multipath effects increase as the sea state worsens.

Ducting is a phenomenon in which radio frequency energy is trapped in or reflected by a “duct” in the atmosphere. Over warm (above about 20° C) bodies of water, ducts tend to be formed and increase in strength when the water and air temperature increases. During marine mobile monitoring, the effects of ducting can cause failure to intercept signals, and also to intercept very distant signals which proceed in the duct with very little attenuation.

3.2.2.6 Satellite-based monitoring platforms

Since conventional fixed or mobile ground-based spectrum monitoring facilities vary from country to country, leading to possible international frequency coordination issues, a solution to provide large scale or global spectrum monitoring can be based on small satellites in low Earth orbit (LEO) as mobile monitoring platforms. While moving along its orbit, the satellite spectrum monitoring platforms can receive signals from ground-based radio emission sources located in different areas. Spectrum data continuously collected across different countries can facilitate international frequency coordination and sharing of spectrum usage information such as frequency occupancy and spectrum maps over time and space. Moreover, satellite-based spectrum monitoring can represent a cost-effective solution for remote areas as well as developing countries where the deployment of an adequate numbers of fixed monitoring facilities can be limited by their implementation costs, thus also facilitating the extension of the International Monitoring System as resolved by Resolution ITU-R 23.

The monitoring architecture can consist of one or more small satellites carrying a payload which receives, detects and process signals from the Earth. The spectrum data collected are then transmitted to ground stations distributed on the Earth where the data are stored and processed to retrieve frequency occupancy and emitter geolocation.

Since a satellite passes over a receiving ground station only for a limited time window, high data rates are required for the satellite-ground stations links.

It should also be noted that not all the signals emitted from the Earth are suitable to be detected from a satellite monitoring platform, since most signals arriving to the satellite platforms can be very weak due to the high propagation loss. In addition, signals with narrow beams are difficult to be captured by moving satellites in LEO and are not suitable for satellite-based monitoring. In general, the frequency bands suitable for satellite-based monitoring go from VHF to Ku frequency band. Further details can be found in Report ITU-R SM.2355 (Annex 1).

3.2.3 Transportable monitoring stations

Transportable monitoring stations combine some of the features and advantages of fixed stations with some of the features and advantages of mobile stations. Similar to mobile and compact monitoring stations, transportable stations provide regulators with a temporary solution for coverage gaps or specific campaigns and events. These stations are advantageous for monitoring from elevated positions, such as the tops of buildings during major sporting events. Mobile monitoring stations often experience multipath interference, whereas portable monitoring stations can mitigate this effect.

Technological advancements and integration have enabled transportable antennas to deliver functionality and performance comparable to those of fixed and mobile stations. These stations typically will have antennas smaller than fixed or mobile antennas as they are specifically designed to be portable. This smaller size antenna aperture may account for different performance specifications especially for low VHF range frequencies. However, because of the portability, the transportable station becomes particularly useful for urban or hard-to-access areas. In densely populated city areas, street-level monitoring measurements are often unreliable; only measurements taken from elevated, dedicated sites, typically buildings, yield accurate results. For such monitoring operations, compact, lightweight, and portable antennas and stations are essential.

FIGURE 3-11

Antenna for portable system

HDB-23-3-11

The transportable or portable configuration provides measurement resources that can be easily moved to locate on the LoS propagation path of the signal. These stations can be configured in many of the same ways as the other configurations however, for reasons of portability typically will have smaller antennas that will reduce the sensitivity especially at lower frequencies.

The equipment for transportable stations is typically installed inside of an equipment shelter, as described in § 2.5.2.2. Shelters may be small, allowing space for just equipment that may be remotely controlled, or may be larger, allowing workspace for one or several operators. VHF/UHF and SHF antennas for transportable stations may be installed on a transportable mast so they may be elevated several meters above the ground.

Transportable stations may include HF DF capability, using transportable antennas that are deployed on an adjacent field. These antennas allow the transportable system to provide high aperture and therefore highly accurate DF results. The antennas can then be removed when it is desired to move the transportable station.

A transportable station may be placed in a particular location, such as on the ground or on the roof of a building, for an extended period of time, and then may be moved to another location as required by the needs of the monitoring service. Such a station does not need a dedicated vehicle as does a mobile monitoring station; a vehicle or other means of transportation is only needed when it is desired to move the transportable station from one location to another.

Typically, this type of monitoring station can be operated local but also remote controlled by the central station. Via communication connection the measurement data can be transferred directly to the central station.

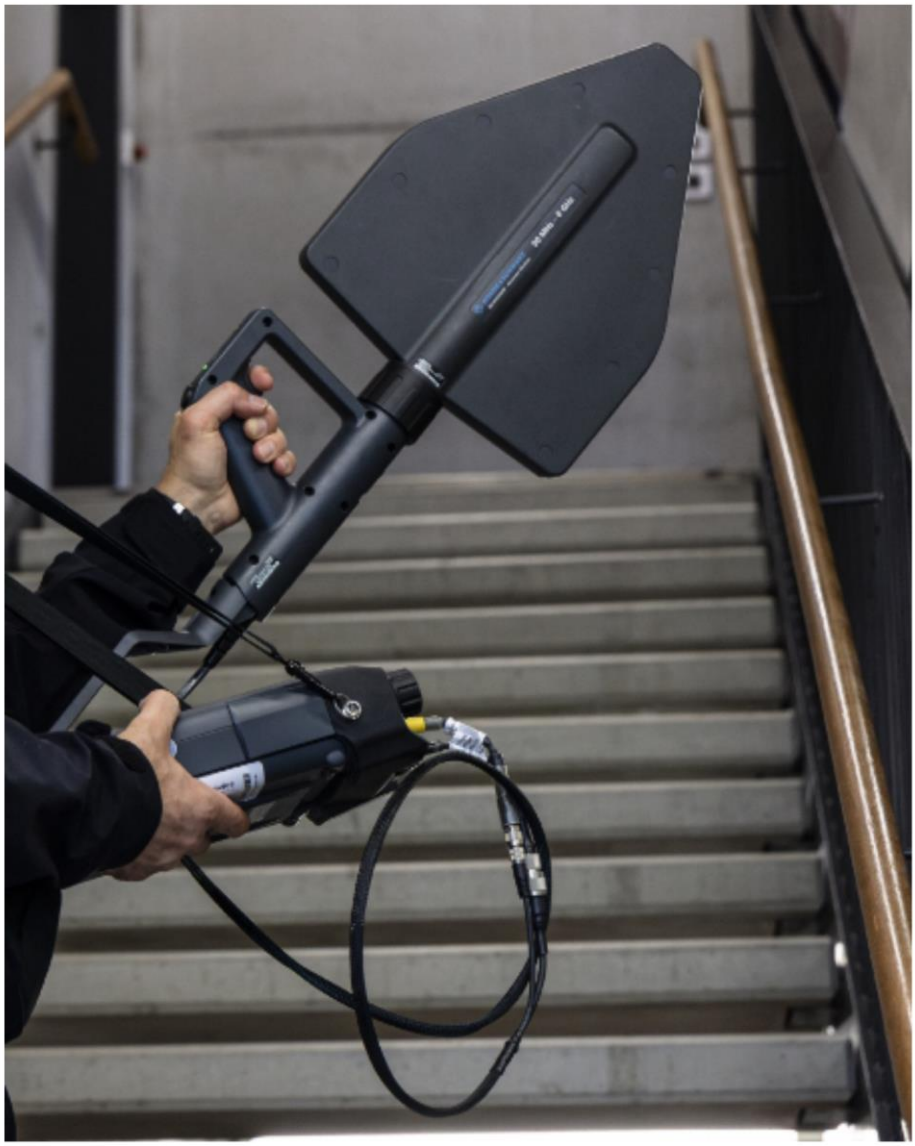
3.2.4 Additional support equipment

3.2.4.1 Portable and handheld monitoring equipment

To provide greater flexibility on monitoring activities, especially mobile monitoring stations, may also be equipped with portable equipment, such as handheld spectrum analysers and small sized measurement antennas, portable receivers and handheld directional antennas. Modern portable equipment typically has its own processor and touch screen to replace the external control devices. According to the design, this equipment could be divided into portable type (the antenna and equipment are separated, the device is hanging in the body of the operator while monitoring) and fully handheld type (the antenna and equipment are integrated, the device could be held in a single hand while monitoring). Their moderate weight makes it possible to carry them walking to locations inaccessible to vehicles, e.g. to the interior of a building or to the roof of a house.

FIGURE 3-12

Portable and handheld monitoring equipment



HDB-23-3-12

Such instruments are necessary to determine the exact location of interference source, or to verify compliance of radio equipment with the relevant technical parameters on site. In particular, handheld monitoring equipment is important for the ground search of interference sources in higher frequency band.

Portable apparatus can be found on the market for field measurements in the frequency range 150 kHz to 30 MHz, with loop antennas directly connected to the receiver input. The accuracy can be better than ± 2dB and the apparatus is quite suitable for monitoring purposes with the object of checking whether the Radio Regulations (RR) are being obeyed. However, when their sensitivity is inadequate for operations involving the measurement of very low field strengths such as those of spurious emissions from a transmitter, narrow-band apparatus of higher sensitivity should be used.

Portable apparatus operating between 20 MHz and 6 GHz or more is available. This portable apparatus can be equipped with a small panorama display and small broadband antennas, which are well suited for portable applications. However, if more sensitive and accurate measurements are required it is essential to use a more sophisticated monitoring receiver or spectrum analyser.

3.2.4.2 Monitoring sensors

The fixed monitoring stations are preferred to install the antennas in the higher height to get wider coverage. Still the buildings and obstacles in cities may cause monitoring blind spots. Smaller, low-cost, high-density deployed monitoring sensors may be introduced as supplement. For the purpose of reduce the cost and maintenance difficulties, the monitoring sensor usually does not have high performance, and the equipment and antenna are designed and integrated as a unit.

Monitoring sensors could be used as the monitoring nodes of the monitoring network, or independently networked by them. All the monitoring sensors in the monitoring network could be controlled together to implement monitoring tasks, such as signal analysis, automatic anomaly detection, TDOA, and 24-hour data acquisition, the monitoring data could be stored for further use.

FIGURE 3-13

Example of monitoring sensors

HDB-23-3-13

3.3 Monitoring and measurement antennas

3.3.1 General considerations

The purpose of receiving antennas is to extract the maximum possible signal from the environment and to apply this signal to the input of the receiver, while at the same time minimizing the pick-up of noise and interfering signals. The specific characteristics of a monitoring antenna will be determined largely by each particular application. When a monitoring antenna is chosen, consideration should be given to such factors as the properties of the desired signal, the parameters intended for observation, the characteristics of the installation site and any interference that may be present.

For the best reception results, antennas should have a polarization corresponding to the polarization of the arriving signal wavefront and should provide matching of the impedance of the transmission line and receiver input circuits, so as to ensure the maximum transfer of power. Omnidirectional reception patterns have proved useful for general monitoring or for radio-frequency spectrum determinations. For the observation of a

particular signal on shared frequencies, it may be desirable to use a directional antenna, which either nulls one or more of the interfering signals, or maximizes the desired signal. A mobile unit is also useful in separating shared frequencies by driving closer to the antenna radiating the signal of interest. For some types of observations, such as studies of field strength, it is considered necessary that the properties of the antenna used be accurately predictable with respect to frequency response and be invariant with time. A mobile unit with calibrated antennas is able to provide a measure of average field strength in a given area. Since no one type of antenna has all the properties necessary for efficient reception of all types of signals, a number of different antennas will generally be required at monitoring stations.

3.3.2 Influence of interference environment

Ideally, monitoring stations should be placed at sites where monitoring is not interfered with by transmitters close by, or by high-voltage lines or microwave links passing across the site. Further, once a site is selected, or more importantly, once monitoring operations have started, the site should be protected by means such as frequency planning.

Since the aforementioned principle cannot always be observed, the antennas and receivers of spectrum monitoring stations generally operate under interference conditions that are generally far more rigorous than those experienced by ordinary communication-receiving antennas and receivers. The working frequency, location, antenna height and azimuth, etc., of a fixed-service receiver are specially selected at the frequency assignment stage such that the receiver in question is adequately protected (by providing an appropriate frequency and a geographical separation between radio stations based, in particular, on the given parameters of the antenna and receiver) from the effects of interference from transmitters of other radio links. Every effort is made therefore to maintain such protection *vis-à-vis* all new frequency assignments.

Spectrum monitoring station antennas should ideally be set up on a raised point surrounded by open space to ensure that signals are received from the greatest possible number of monitored transmitters within a wide service area and for all azimuths. It often happens that monitoring stations are located in cities close to powerful transmitters – including those used for sound and television broadcasting – with high antennas, or that such power transmitters are installed close to existing monitoring stations. In such cases, little or no attention is ever paid to the question of observing the frequency and geographical separation requirements that are a fundamental feature of frequency planning for communication radio facilities. As a result, monitoring station antennas and receivers generally have to operate under far more rigorous interference conditions than other radio facilities. This imposes special requirements in terms of the parameters characterizing the intrinsic protection of receivers and active antennas against the effects of potential interference.

These requirements concern parameters such as receiver selectivity and linearity (second-and third-order intercept points), IF and image frequency rejection, receiver dynamic range and linearity (second-and third-order intercept points) of active antennas and their protection from interference (damage threshold). The above, to a large extent, determines the ability of the spectrum monitoring station equipment as a whole to perform measurements and DF under arduous uncontrolled interference conditions. If, as a result of insufficient protection due to a failure to observe the requirements indicated in §§ 3.3 and 3.4, the antenna and/or receiver is affected by interference, both the measurement of certain (or all) transmitter emission parameters and DF operations can be subject to significant errors; in other words, the data will be unreliable or may simply be unobtainable. Therefore, when antennas and receivers with inadequate characteristics are used, the large sums spent on setting up the spectrum monitoring stations and networks may have been wasted. The influence of interfering signals usually appears as intermodulation and/or blocking. The mechanisms of these phenomena are considered in § 3.4.2.

In the light of the foregoing, it is recommended to avoid the use for spectrum monitoring purposes of standard receivers that do not satisfy the full set of requirements laid down in §§ 3.3 and 3.4.

Results of measurements and DF at the site are also greatly influenced by other antennas and surrounding metallic structures; this subject is discussed in § 3.3.6.

3.3.3 Suitable antenna configurations

The properties of electromagnetic waves, including wavelength, resonance and signal and noise propagation, help determine choice of antennas in relation to:

– Directivity and gain, which are the main technical parameters of antennas. Antennas may be divided into two groups: omnidirectional antennas (where the azimuth radiation pattern is essentially circular) and directional antennas. Omnidirectional antennas may be used for general tasks of monitoring when the transmitter position is not known (occupancy rates, scanning), while directional antennas may be used for specific tasks (technical measurements) when better sensitivity is needed.

– VLF, LF, HF, VHF, UHF or SHF frequency bands.

– Size and weight may be considered when choosing an antenna, depending on the type of monitoring station: fixed, mobile, transportable or portable.

3.3.4 Antennas for VLF, LF, MF and HF

For VLF, LF, MF and HF frequency bands, the wavelength is very long and it is not practical to have antennas of a size of the order of a quarter wavelength, which would give maximum antenna sensitivity. Active antennas could be used, but they have lower linearity due to intermodulation.

An antenna system that will provide omnidirectional vertically-polarized reception over the short-wave frequency range (2 to 30 MHz). This system could consist of one large antenna such as a wideband inverted conical antenna, several conical monopole type antennas that overlap in frequency, or an active antenna.

Antenna size is the principal limitation for VLF/LF/MF/HF mobile monitoring stations. Such stations allow for:

– Measurement results when moving near the transmitter. For example, whereas a fixed monitoring station may not be able to perform an accurate measurement because the *S*/*N* is too low, a mobile monitoring station can be driven near the transmitter to increase the *S*/*N*.

– An additional line-of-bearing (LOB), in association with a fixed monitoring station, to increase location accuracy.

Size limits considerably the choice of such antennas:

– Short monopole (whip antennas)

– Dipole (centre-fed)

– Magnetic loops

– Active antennas.

General considerations for HF antennas

At HF, the radio waves reflect off the ionospheric layers that exist from 100 to 300 km above the Earth. The antenna should direct maximum radiation at these ionospheric reflecting layers at the desired elevation and azimuth angles, such that coverage to desired locations will be achieved.

For instance, if a transmitter location is 350 km from a monitoring station, maximum radiation from the antenna should occur at an elevation angle near 60 degrees for reflection off the 300 km-high ionospheric layer. In this case-the ray path from the monitoring station to the ionosphere and then to the transmitter forms an approximate equilateral triangle, including a direct line between the monitoring station and the transmitter; this simple one-reflection path is called a one-hop path. As the distance increases, the elevation angle or take-off-angle for the one-hop path decreases; the take-off-angle of the one-hop ray can get as low as about 3 degrees for the longest paths. Three degrees is typically a minimum take-off-angle, being limited by nearby hills, other obstructions and antenna radiation pattern undercutting at the very low elevation angles. In general, the path to the receiver may consist of several hops; for instance, a two-hop path occurs where there is a ground reflection midway between the transmitter location and the monitoring station and there are two reflections from the ionospheric layer. The one and two hops may exist singly or simultaneously. When two or more paths occur at the same time, this is known as multipath propagation.

It should be noted that horizontally polarized signals do not propagate along the earth's surface. Therefore, horizontally polarized HF receiving antennas are limited in their usefulness. Any signal launched either horizontally or vertically at the transmitter will have a horizontal and vertical component at the receiver site when it is reflected off the ionosphere (by skywave). Therefore, a vertically polarized monitoring antenna is more useful for receiving signals that are coming from the horizon or by skywave.

A highly efficient receive antenna is generally not needed because of the moderately high levels of manmade and atmospheric radio noise at HF. For instance, one might wish to use a vertically-polarized antenna for reasons of radiation pattern coverage and accept a few dB of antenna loss because this antenna loss usually will not have a significant effect on the receive system sensitivity.

For receiving, it is much more important to use antennas with a high directive gain so that the signal level picked by the antenna is enhanced relative to the noise. Under the assumption that equal noise power density is being received from all directions, which is usually the case, the total noise power received by the antenna is independent of the antenna directivity. Thus, the received *S/N* is increased by increasing receive antenna directivity.

A given monitoring station may be able to use several antennas to provide required short- to long-range coverage. Antenna selections may include a short-range omnidirectional high take-off angle antenna combined with several moderate- to long-range directive antennas. Also, a monitoring station may have limited land area available and may need to use a small number of antennas of a single type that provide the best service to all ranges. Several ground station antenna types are presented in this section that may be chosen for use by a monitoring site. All HF-high power transmitters (>1 kW) should be located at least 5 to 10 km from the monitoring station in order to provide high isolation between HF transmitters and HF receivers and to allow a lower radio noise environment at the receive site. Antennas for HF should cover the 2 to 30 MHz frequency band.

3.3.4.1 VLF/LF/MF/HF omnidirectional types

In view of the extremely long wavelengths at VLF, LF and MF (e.g. 10 000 m for a frequency of 30 kHz), antennas for these frequencies are necessarily limited to those that are small compared to the wavelength. Since signals in these bands are primarily vertically polarized, vertical antennas are generally used for reception. A simple upright antenna, which represents only a small percentage of a quarter wavelength, has an impedance which is largely reactive and of large magnitude. Such an antenna can generally be made tall enough to provide required sensitivity above atmospheric noise levels.

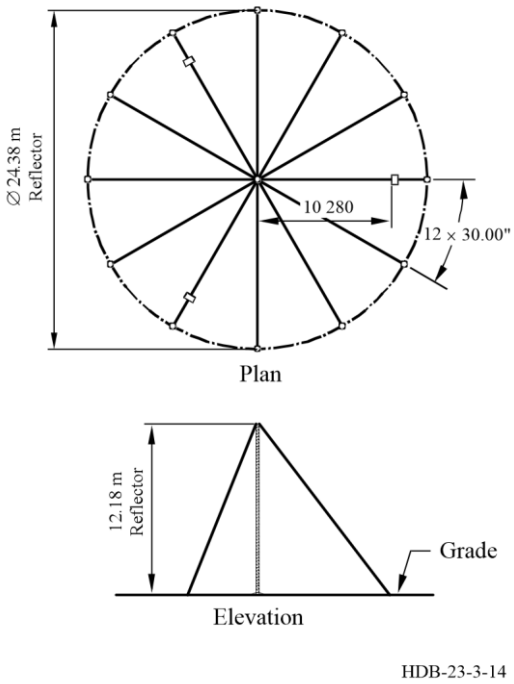
When the size of the antenna element is limited physically to a small part of a wavelength, such as occurs at VLF and LF, an active antenna will generally provide a much greater *S/N* than that obtained by connecting the antenna directly to the receiver without the use of an active device for impedance matching. In order to avoid intermodulation and cross modulation in the active circuits, attention should be paid to the following technical data:

Antenna factor 20 log(E/V) should lie between:	10
Second-order intercept point (antenna output) should be not less than:	50 dBm
Third-order intercept point (antenna output) should be not less than:	25 dBm
Permissible field strength for 10 dB cross modulation should be not less than:	10 V/m
Maximum permissible r.m.s. value of the interfering field strength (lightning protection damage threshold) should not be less than:	20 kV/m at 100 kHz 200 kV/m at 10 kHz

State-of-the-art active antennas fulfilling the above given specifications are offered by several manufacturers. In high local field strengths, which are common in medium wave as well as FM and TV bands, even the above specifications for active antenna are not adequate and one should resort to a passive antenna such as a 12 m tall monopole shown in Fig. 3-14.

FIGURE 3-14

Typical passive receive antenna for VLF/LF/MF/HF, 9 kHz – 30 MHz



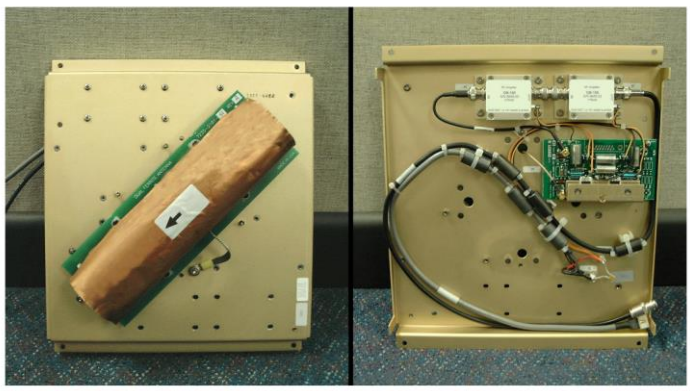
3.3.4.2 VLF/LF/MF/HF active antennas

The chief limitation on antennas for mobile monitoring stations is their size. Owing to the inevitable lack of space, antennas must be small. Therefore, antenna size in the case of the lowest frequencies represents only a very small fraction of a wavelength. Loop antennas covering the frequency range 9 kHz to 30 MHz are available with or without ferrite material, and by reason of their clearly defined electrical characteristics, are particularly suitable for field-strength measurements and DF of ground wave signals.

One example of a compact active antenna, which is useful for both monitoring and DF purposes, is a pair of small active magnetic loops; top and bottom views of one of the pair of loops are illustrated in Fig. 3-15. This antenna can be quite small (box with sides approximately 0.3 × 0.3 m and 0.1 m high) to cover 300 kHz to 30 MHz, but has the sensitivity and azimuth DF accuracy of a much larger antenna (such as an array of 3 m-tall whips).

FIGURE 3-15

Compact active antenna



HDB-23-3-15

Each loop consists of a high permeability ferrite rod wound with a multiple turn coil. The coil is shielded with an electrostatic shield, and the outlet is connected to a transformer –to make the antenna less sensitive to local e-field disturbances and thereby improve DF accuracy. The transformer provides impedance matching, common mode rejection, and balance to unbalance transformation.

Active antennas covering VLF/LF/MF/HF frequencies (9 kHz to 30 MHz) can also be built for horizontal polarization as well as for vertical polarization, as shown in Fig. 3-16. The antenna provides two output connectors, one for vertical polarization and one for horizontal polarization. It covers 9 kHz to 80 MHz vertically polarized and 600 kHz to 40 MHz horizontally polarized.

FIGURE 3-16

Active antenna for vertical and horizontal polarization

HDB-23-3-16

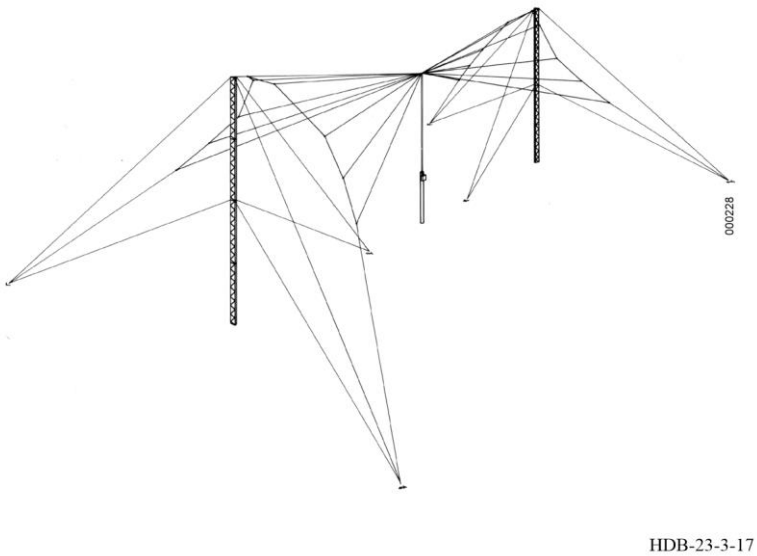
3.3.4.3 HF directional antenna types

Horizontal broadband dipole (see Fig. 3-17)

The best antenna types for short to moderate range HF coverage are horizontally or circularly-polarized antennas that have peak radiation near the zenith. The ground wave radiated by a vertically-polarized HF antenna is attenuated by ground losses and generally not received farther than about 100 km over ground and about 300 km over ocean water. All vertically-polarized antennas have a null overhead and are not suitable for very short-range skywave monitoring at HF. The horizontal wideband dipole is an example of an antenna that can provide short-range coverage, from approximately 3 to 12 MHz, with a fairly omnidirectional radiation pattern. These antennas are relatively small; an example of such a horizontally-polarized dipole is mounted on two towers, 22 m tall and requires 66 m × 38 m of land area; this is a good antenna to use on a limited receive or transmit site. The gain of this antenna is typically 5 dBi or higher. For significant higher gain values, horizontally-polarized log-periodic antennas can be designed to provide short range coverage with a fairly omnidirectional radiation pattern for low frequencies changing to more moderate- to long-range coverage and directional behaviour for higher frequencies.

FIGURE 3-17

Broadband horizontal dipole – short to moderate range

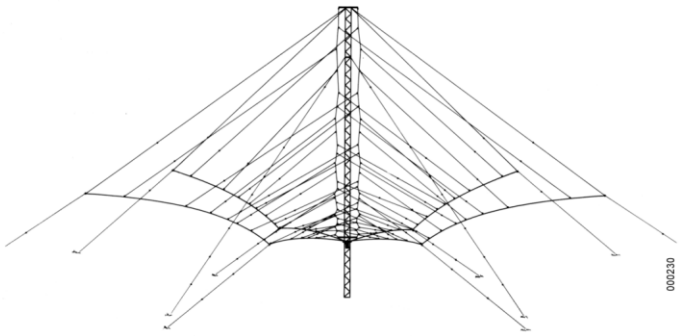


Omnidirectional circularly-polarized LPA (see Fig. 3-18)

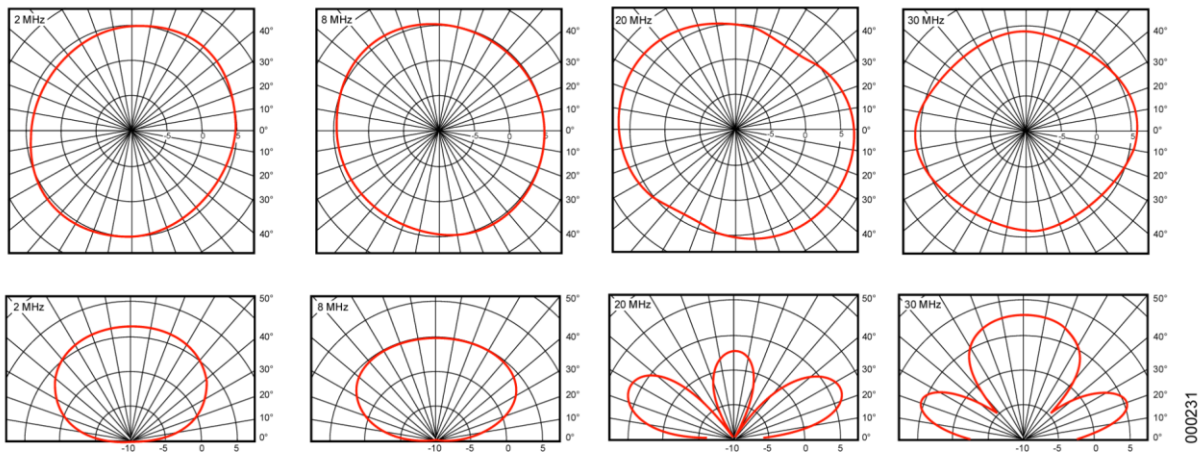
An antenna type that provides omnidirectional coverage over the entire HF band is a circularly-polarized log-periodic antenna (CPLPA). This antenna has the advantage of providing short- to moderate-range communications from one structure. At the lower frequencies the antenna radiates at the higher elevation angles for shorter-range coverage and at the higher HF frequencies the take-off angle is lower for reception from longer ranges. This antenna is supported by one tower and has two sets of orthogonal log-periodic dipole arrays, each dipole being a centre-fed inverted Vee connected to feedlines supported along the sides of the tower. Tower height is 28 m and requires an area of 94 m × 94 m. The gain of this antenna is 5 dBi.

FIGURE 3-18

Circularly-polarized log-periodic omnidirectional antenna (short to moderate range)



Azimuth patterns at elevation angle of beam maximum (gain (dBi))



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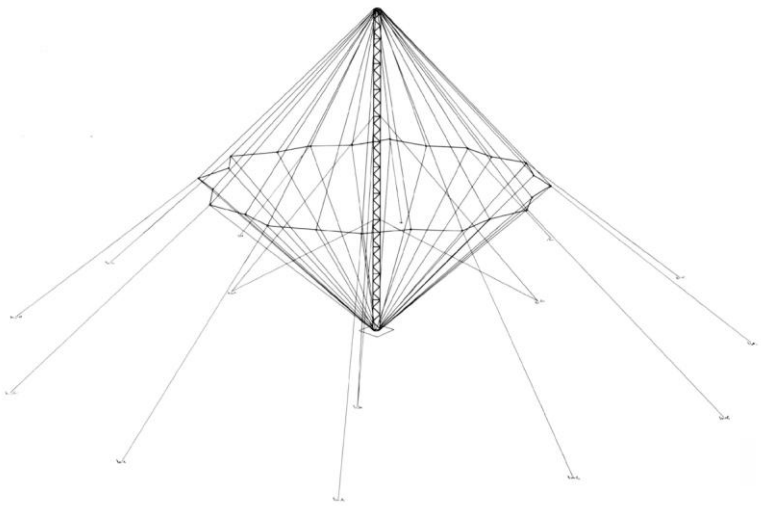
Vertically-polarized broadband monopole omnidirectional antenna

This antenna is a broadband omnidirectional antenna that can be used to receive short-range ground wave and moderate- to long-range skywave. A typical vertically-polarized broadband monopole is shown in Fig. 3-19. This antenna for the 3 to 30 MHz frequency range is 25 m high with a diameter of 52 m. The vertically-polarized broadband monopole and CPLPA have nearly equal gain at low frequencies at the lower take-off angles; however, the CPLPA is superior at the higher frequencies.

FIGURE 3-19

Broad and vertical omnidirectional antenna – moderate to long range



HDB-23-3-19

Loop arrays

Electrically small, inefficient antennas such as loop antennas can be used to advantage in a wide range of receiving applications in the HF frequency range. Noise caused by antenna inefficiency has the same effect as other sources of noise on the *S*/*N*. When external noise is greater than the noise from antenna inefficiency (and internal electronics, if present), an antenna is said to be "externally noise limited". The internal noise of an externally noise-limited antenna is relatively insignificant, since the greater external noise source determines the system's *S*/*N*. When external noise is relatively high, small receiving antennas work as well as the full-size fully, efficient antennas.

The basic loop is a large low-inductance aluminium tube. It is fed at the upper mid-point via a broadband, passive matching network. One advantage of loops over dipoles is their lower input impedance. The loop's performance is comparatively unaffected by nearby conducting bodies such as trees, buildings and snow. Moreover, since the radiation resistance of electrically small antennas is low, mutual effects are generally insignificant, enabling loops to be configured in various arrays that tailor their performance to particular receiving requirements.

The azimuthal pattern of a single loop is a figure eight at the horizon, increasingly omnidirectional at higher angles of arrival, and virtually independent of azimuth at angles of arrival above 50 degrees. Signals from multiple loops can be combined in phase, or "beam formed". The resulting pattern is directional, with a bearing corresponding to one of the array directions. The directional pattern has its maximum gain at some angle below the zenith. Increasing the number of loop elements, increases gain and directivity. While this directional pattern is useful for monitoring, if an array of loop elements is used for DF, the elements should not be combined, so that the response of each element may be separately measured.

Beam forming is accomplished by bringing the feed cables from each element in an array to a delay/combiner unit, or beam-former, located at the array's physical centre. In unidirectional beam forming, signals from each element are delayed by means of appropriate lengths of coaxial cable, or delay lines, then summed in a combiner. In bidirectional beam forming, the signals are split and fed into two separate sets of delay lines, then summed in two separate combiners.

Multiple small arrays are often combined in rosette configurations. One common rosette consists of four bidirectional arms equally spaced in azimuth with a common centre, as shown in Fig. 3-20. Each arm consists of eight loops. This four-arm, 32-element loop configuration can produce eight beams, one for each 45 degrees of azimuth.

FIGURE 3-20

Four-arm, 32-element loop array

HDB-23-3-20

3.3.5 Antennas for VHF, UHF and SHF

The propagation conditions encountered in the VHF and UHF bands generally restrict reception to near LoS distances. In order to increase the reception area coverage, the VHF and UHF antennas are usually mounted at the top of a tower positioned near the monitoring building. In this manner, coaxial line losses, which can become high at these frequencies, are kept to a minimum.

Antenna size is less critical in these bands (except for the lower VHF band where the dimensions of the antenna have a direct impact on the sensitivity). Fixed and mobile antennas have similar characteristics; the main difference is the position of the antenna and the ability to put it on the top of a mast.

The types of omnidirectional antenna encountered in these bands include dipole, conical or biconical antennas. Directional antennas may also be used, such as those for DF systems.

Directional antennas may improve technical measurement by reducing noise and interference and provide increased coverage and *S*/*N* for general monitoring and DF tasks. Individual directional antennas may be on a rotator or may use fixed arrays of directional antennas covering all directions, such as an outward looking circularly disposed antenna array. Fixed arrays with directional or omnidirectional elements are suitable for a VHF/UHF DF system.

3.3.5.1 VHF and UHF omnidirectional antenna types

Omnidirectional antennas have a radiation pattern that is not directional in azimuth. Figure 3-21 (a) shows an omnidirectional receiving antenna. The antenna is designed as a monitoring antenna for vertical polarization in the frequency range from 20 MHz to 8 GHz. The antenna consists of a shunt fed monopole operating in the frequency range from 20 MHz to 200 MHz and a bi-cone antenna for the frequency range from 200 MHz to 8.5 GHz. The two frequency subranges are accessed using an RF switch to minimize losses caused by a combiner or diplexer. The bi-cone concept delivers superior radiation characteristics even without the presence of a ground plane. Main application is sensitive monitoring in stationary installation.

Figure 3-21 (b) shows an active omnidirectional receiving antenna. The antenna is designed as a monitoring antenna for vertical polarization in the frequency range from 20 MHz to 8 GHz. The antenna consists of an active dipole operating in the frequency range from 20 MHz to 1.1 GHz and a passive antenna with low-noise preamplifier for the frequency range from 1.1 GHz to 8 GHz. The two frequency subranges are combined by a diplexer. The dipole concept delivers superior radiation characteristics even without the presence of a ground plane. The integrated preamplifier provides good reception. Main application is sensitive monitoring in stationary or mobile installations where it offers good reception results despite its compact size. The antenna is powered by a supply unit.

Figure 3-21 (c) represents a passive broadband omnidirectional antenna. The antenna is used to detect and monitor mobile radio and microwave signals with high sensitivity. The linearly polarized antenna covers the frequency range from 800 MHz to 26.5 GHz. The radiation elements of the antenna consist of two symmetrical, coaxially fed aluminium shells. At frequencies of less than approximately 7 GHz, their functional principle corresponds to a broadband dipole (biconical antenna), at higher frequencies it changes to an excitation mode similar to that of a horn radiator. The mechanical stability of the antenna is provided by a support tube made of aluminium and bonding within a foam cylinder. The aluminium base plate provides additional decoupling of the antenna from the underlying structure at the installation site. The low-weight antenna requires little

space and is easy to handle. By using a low-attenuation, weatherproof radome, reliable operation of the antenna is ensured even in harsh environments.

FIGURE 3-21

Broadband omnidirectional receiving antennas

HDB-23-3-21

3.3.5.2 VHF and UHF DF antenna types

Examples of monitoring and DF antennas are shown in Fig. 3-22.

An antenna used in the VHF/UHF range is the broadband omnidirectional biconical antenna illustrated in the left of Fig. 3-21. This antenna may be supplied along with a nine-element fan array, also illustrated in the Figure, to provide DF coverage. It is available in either vertically polarized or dual-polarized versions (vertically polarized is illustrated); the dual-polarized version has separate outputs for vertical and horizontal polarization. A smaller, compact and light-weight version is available for portable applications, or it can be placed on the roof rack of a standard passenger automobile in what looks like a piece of luggage to provide an inconspicuous mobile monitoring station. Both configurations provide very good coverage over a 150 to 1 frequency range of 20 to 3 000 MHz, the smaller one with somewhat reduced sensitivity at frequencies below 100 MHz.

The combination of the biconical antenna and the nine-element fan may be used for monitoring and DF over the entire VHF/UHF range in both fixed and mobile applications; however, for improved sensitivity and accuracy at fixed sites, an additional, physically larger array, consisting of a five-element VHF vertical dipole array may be used.

The DF antenna shown on the right covers the frequency range from 20 MHz to 8.5 GHz (vertical polarization) and 20 MHz to 7.5 GHz (horizontal polarization) for fixed, mobile, and transportable applications. Switchover from active to passive mode is possible for the frequency range from 20 MHz to 1 300 MHz. This antenna also contains an omnidirectional monitoring antenna output that supports the frequency range from 20 MHz to 8.5 GHz. Due to the exceptionally large number of antenna elements, this DF antenna is robust against reflections and ensures reliable DF results even with strong multipath propagation.

FIGURE 3-22

Examples of VHF/UHF antenna elements (enclosures removed)

HDB-23-3-22

For optimum performance in applications requiring high dynamic range (good sensitivity and low distortion), the antenna should use passive antenna elements followed by active RF switching and preamplifiers. Use of passive antenna elements ensures that the antenna will be free of parasitic responses, has well behaved patterns and gain/phase response for DF accuracy, and does not produce distortion (IM or harmonic), a common problem in active element antennas. One should consider that active antennas might present parasitic responses, producing distortions such as IM and harmonics, lower MTBF and varying performance with aging, although they also present benefits such as broader range and larger antenna gain for a smaller size and lower weight. One should also consider the intended use, and the local of installation such as the benefits and drawbacks of each technology is properly considered.

For some applications it may be desirable to have the benefits of both active and passive antenna elements. The DF antennas shown in Fig. 3-23 have antenna elements that can be switched between active and passive operation by mouse click. Since active operation offers better sensitivity, this is the default setting. In case very strong signals appear in the spectrum, the antenna can be switched to passive mode to minimize intermodulation problems.

FIGURE 3-23

Examples of VHF/UHF (20-6 000 MHz) antenna arrays

HDB-23-3-23

As an example, one could consider the installation of a monitoring station in urban areas with large spectrum use. Such installation might be desirable to monitor low-level transmissions that might not be detectable from even very sensitive stations and theoretically perfect sites located outside the urban centre. Due to high RF levels on urban centres, active antennas and broadband switching devices used in monitoring stations might have their performance and effectiveness strongly affected on these sites, pushing the demand for passive use of passive antennas and/or even filters and more band selective systems, such as to avoid interference.

However, passive element antennas suffer from poor sensitivity unless they are physically large and are built in multiple bands that are optimized for relatively narrow frequency ranges. This could result in a complex antenna structure that is difficult to install and maintain. Rather, if very high dynamic range RF preamplifiers and RF switching circuitry follow the passive elements, the antenna can cover a wide frequency range and also provide good sensitivity. This is possible if both the passive antenna elements and the active RF amplification operate at the same impedance, where it is possible to build the preamplifiers and switches with very high dynamic range and broadband response.

The high dynamic range RF switching and pre-amplification circuits should be physically mounted in the antenna, to eliminate the need for phase-matched RF cabling between the antenna and the rest of the system when used for DF, and to provide line amplification near the signal source to overcome cable losses that would otherwise increase the system noise figure and thereby degrade sensitivity. The RF preamplifier used in the antenna should have RF performance characteristics that substantially exceed that of the receiver to which it is connected, because the RF preamplifier must handle the entire VHF/UHF spectrum while the receiver typically has pre-selector filters that limit the amount of RF signal energy that the receiver RF front-end circuitry must handle.

Improvement of antenna characteristics in this case is reached by high-frequency cable length reduction to a minimal value, considering that this cable is the main source of noise in transferring received signals from antenna elements to a radio receiver. The placement of IF converters in the immediate proximity of antenna elements allows for the elimination of the effect of a cable on the antenna (which, in this case, transfers IF signal) and also to transmit IF signal to distances up to several hundred meters. It results in increasing sensitivity and dynamic range of a system.

With modern receiver designs, the whole frequency conversion from V/U/SHF frequencies to digital I/Q data can be achieved in proximity to the antenna itself, thereby eliminating the need for long, lossy coaxial cables. This improves system sensitivity.

3.3.5.3 VHF and UHF directional types

In VHF and UHF bands, the need for antennas that have low-voltage standing wave ratio (VSWR) and uniform patterns has led to the development of arrays with a series of elements whose characteristics repeat according to the logarithm of frequency (log-periodic). These arrays can be made to achieve a moderate gain (10 dBi typical) with good directivity (a front-to-back ratio of 14 dB is typical), and a pattern that remains uniform over a frequency range of up to approximately 10:1. The radiation pattern is typically broad, approaching that of a dipole reflector-director antenna for most frequencies. The uniform gain, pattern and impedance characteristics of the antenna make it suitable for combining together to form a broadband array, for use where highly directional antennas are desired. In particular, the log-periodic antenna serves well as the illuminator for parabolic reflectors at UHF, where very narrow beamwidths are desired.

This antenna is generally constructed of a series of radiating elements, which are fed by, and positioned along, a central transmission line. The individual dipole pair elements are each designed to have the required antenna properties over a narrow part of the entire operating frequency band, and to maintain their characteristics as uniformly as possible over their active frequency range. The individual elements are repeated at intervals, which are constant with the logarithm of frequency. The number of intervals depends on the required gain and VSWR of the completed antenna design.

The overlapping of the characteristics of the individual elements of the array produces an active zone consisting of several adjacent elements, which progresses smoothly along the structure as the frequency is varied. The voltage standing wave ratio of the antenna is directly dependent upon the number of elements in the active zone of the antenna at a particular frequency and their efficiency in coupling energy between the electromagnetic wave and the transmission line.

Complete log-periodic antennas are available from a number of manufacturers for both wideband use and for narrow-band special services. Detailed design information is available in publications listed in the Bibliography and in other sources.

A wide variety of directional and DF antennas are available for frequencies above 30 MHz, including wideband or narrow-band Yagi antennas, tuneable dipoles, folded dipoles, biconical antennas and log periodic antennas.

Most antennas for mobile stations are mounted on the vehicle. A reflector antenna for frequencies above 1 000 MHz is shown in Fig. 3-24. In all frequency ranges, active antennas may be used considering their technical data and their limitations, which are given in the discussion above dealing with omnidirectional antennas. Hand carried active antennas (see Fig. 3-25) may be used for the purpose of monitoring, field strength measurement, or even DF.

FIGURE 3-24

Transportable microwave antenna

HDB-23-3-24

FIGURE 3-25

Hand-held directional antenna

HDB-23-3-25

3.3.5.4 Antennas for frequencies above 3 000 MHz

To achieve the necessary high antenna gain for monitoring over long distances, primarily “dish and feed” antennas are used. The gain depends on the relation between dish diameter and wavelength, and on the aperture efficiency of the antenna. A principal alternative to the use of “dish and feed” antennas is the frequency extension of some VHF/UHF antennas to provide coverage of the lower portion of the SHF band.

For an optimized antenna system in the SHF range, several parameters have to be taken into consideration: narrow-band, broadband application and general monitoring or surveillance of signals.

For monitoring and surveillance, high gain and a broad beamwidth for picking up the signal is required. In this case, a common method is focusing or defocusing the antenna feed by means of a motor-driven mechanical equipment. Variation of the beamwidth between 1:4 and 1:10 is possible.

For broadband applications, either linearly, dual linearly log-periodic antennas, conical spiral or cavity backed antennas may be used, the latter primarily for circular polarization. The broadband feeds, based on the log-periodic principle, do not have a constant phase centre. The phase centre moves from the shortest to the longest radiator of the structure, depending on the frequency. If the structure is positioned in the reflector for a certain frequency, defocusing will occur for the others. Optimization based on the calculation of additional

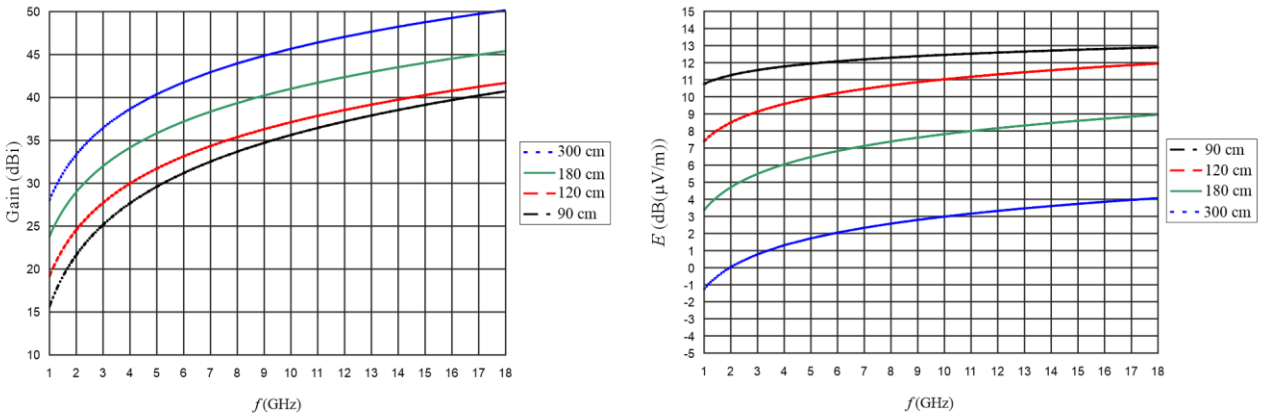
parameters (e.g. length/diameter) allows to minimize losses caused by defocusing. To avoid these losses mechanical focusing, as described above, may be used.

Another solution is to use a special contour for the reflector, which is not perfectly parabolic. In this case, the antenna gain will increase. and the beamwidth will decrease up to a certain frequency, then both will be nearly constant (see Fig. 3-26).

Additionally, the use of broadband fan elements can be used even at SHF frequencies above 3 000 MHz to provide directional radiation patterns with a constant phase centre, making this an ideal element for direction finding purposes.

FIGURE 3-26

Gain and lowest measurable field strength for reflectors with different diameters and linear feed



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For general monitoring, the antenna systems are installed on high-accuracy mono- or bi-axial positioners. Depending on the diameter of the antenna reflector, dimensions and costs may be highly different if operation and survival for high wind speeds is required. For terrestrial monitoring, mono-axial positioners with rotary joints or with cable twist equipment are used. The latter is limited by the azimuth rotating range (e.g. 360°). The elevation can be adjusted manually or remotely controlled within ±10°.

3.3.5.5 SHF band

In the SHF higher frequency portion of the band, some omnidirectional antennas have very poor gain, and the higher propagation loss requires the use of high gain antennas. So that, in this band, monitoring antennas are usually very directional; omnidirectional antennas and fixed antennas need to be in the main beam of the signal to be useful. SHF monitoring, where propagation requires high gain antennas with rotators the directional antennas should be very accurate as the rotation of the antenna requires time to steer the antenna to the direction of arrival.

Mobile omnidirectional antennas are usually used only for the lower frequencies of the SHF band (e.g. frequencies up to about 6 GHz), where they are often used for monitoring mobile operators and analysis of cellular networks.

Due to propagation loss at these frequencies, directional antennas are well suited for SHF bands, because of their high gain. Their main disadvantage is the directivity of the incidence signal, which means that the measurement should be performed on the main beam of the signals.

Mobile stations are particularly important for monitoring at microwave frequencies. Microwave communication signals usually propagate in very narrow, well-defined beams designed for point-to-point, or point-to-multipoint communication. Therefore, it would be very unlikely for a fixed station to be located close enough to a microwave path, so as to be able to intercept a microwave communication signal. Because of its high cost and very limited benefit, it is not recommended to install microwave intercept at a fixed station; instead, this equipment should be in a mobile vehicle or portable configuration. For a dedicated vehicle, a

complete system could be implemented to carry out measurements from 1 to 40 GHz and above. The SHF antenna system shown in Fig. 3-27 consists of the following elements:

– antenna system;

– automatic positioning system;

– antenna monitoring unit;

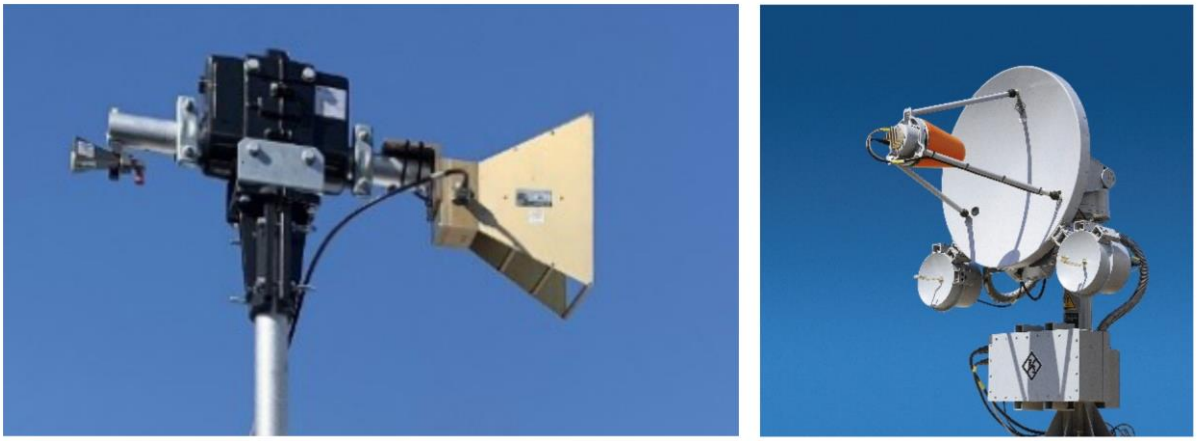
– output antenna cable;

– azimuth and elevation control unit.

The antenna system could consist of several antennas to monitor the full band. Moreover, to ensure flexibility in SHF measurements, considering different measurement situations and the low level of SHF signals, it is useful to include, close to the antenna system, some accessories like LNAs and YIG filters.

FIGURE 3-27

Example of a SHF monitoring system



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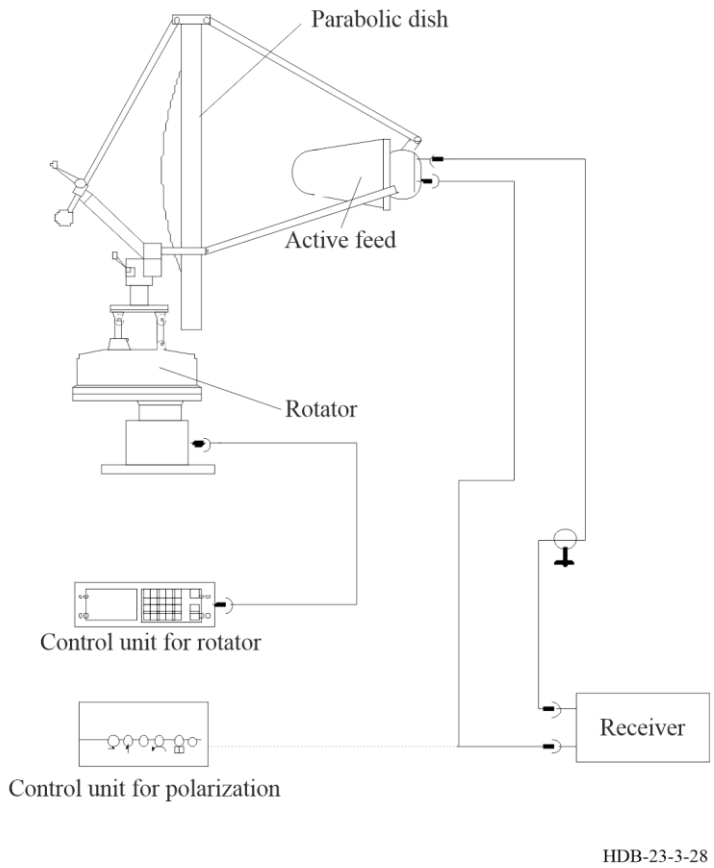
The motor-driven positioners are remotely controlled via control units with different possible operation modes, e.g. variable speed, presetting of positions, scanning and antenna selection. Parallel and serial computer interfaces are provided for system integration. Figure 3-28 shows a typical block diagram. It is highly recommended to install low-noise amplifiers (LNAs) close to the feeder to avoid additional attenuation and noise caused by cables. These combinations are available as so-called “Active Feeds”, either with broadband preamplifiers (e.g. 1 to 18 GHz) or with amplifier units switchable in frequency ranges of one octave.

FIGURE 3-28

Block diagram of steerable microwave antenna 1-18 GHz



Therefore, control units for remotely controllable polarization and frequency range are provided too. Additional features are switchable bypass, attenuators and built-in limiters. It is also recommended to install converters of the receiving system close to the antenna to achieve best system performance.

A compact solution to measure the SHF band from 1 to 40 GHz and above, consisting of several horns and a single tripod, is described as follows:

In the 1 to 18 GHz band, to avoid a large contribution of noise, selective filters should be used and the LNA gain should be limited (less than 20 dB). In the band 18 to 40 GHz and above, measurements results could be improved using waveguides. As waveguides are by definition band-pass filters, higher gain amplifiers could be used.

Taking into account these considerations, a typical example of a handheld system is illustrated in Fig. 3-29. It consists in a suitcase that contains a selection of horn antennas with amplifiers, filters, power supply, batteries and cables to carry out measurements.

FIGURE 3-29

Typical compact solution to carry out SHF measurements

HDB-23-3-29

3.3.6 Siting of antennas

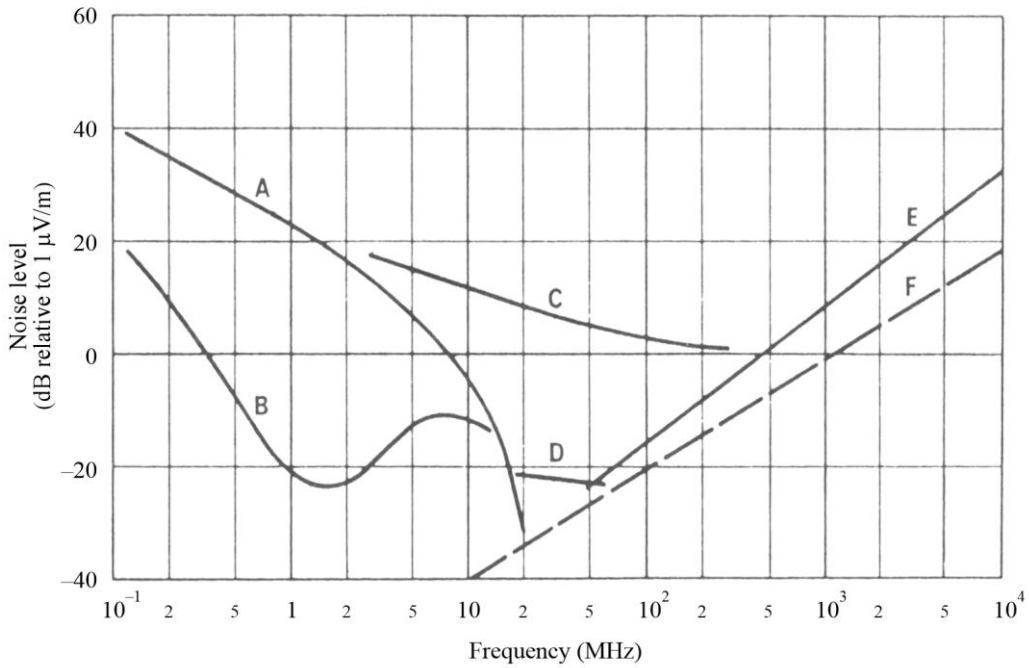
There are three primary considerations that should be examined when a site for monitoring station antennas is being chosen: the interfering noise level, the effects of terrain on the performance of the antennas, and the influence of other antennas and metallic structures or objects nearby. These factors should all be considered before a suitable antenna location and layout are established. Influence of nearby metallic structures such as antenna masts and mast guys should be considered during the design of the antenna structure. Other factors, such as economic, administrative and environmental considerations, will influence the location and layout of the monitoring station itself.

Noise that interferes with the reception of radio waves may be divided into two general categories: natural and man-made.

Natural noise is that produced by the various mechanisms of nature, both on the Earth itself and in neighbouring celestial systems. The major component of natural noise generated on the Earth is the static discharges resulting from the many storm centres, which are almost continuously active on the globe. Storms are most active in the equatorial regions, and their noise is radiated toward the poles, resulting in atmospheric noise components that are largest at the equator and smallest at the poles. High-energy, galactic noise sources exist in the sky (in particular the constellations of Sagittarius and Cassiopeia) and may constitute a considerable portion of the noise picked up by antennas, which are located in an environment where the atmospheric noise levels are low, e.g. at higher latitudes. As shown in Fig. 3-30, cosmic noise is for most frequencies generally masked by other sources, but it can be significant in some cases, particularly if the receiving antenna happens to have a lobe oriented in the direction of a strong source.

FIGURE 3-30

Typical average noise level in a 6 kHz bandwidth (frequency range, 100 kHz to 10 GHz)



Interference to reception from man-made sources may take many forms (see also §§ 2.5.3 and 5.3). One of the most important sources to avoid when choosing an antenna site is a nearby broadcasting station. Even though the operating frequency of the station may be very different from the proposed monitoring frequencies, there can be significant interference caused by radiation of spurious emissions and harmonics of the principal frequency, and production of intermodulation or other responses caused by the overloading of the receiver's radiofrequency, intermediate-frequency and audio-frequency circuits. Receiver desensitization may also occur, even if spurious response is not noted. Additionally, with the advent of cellular phone systems with multiple service providers sharing the same tower, receiving sites in close proximity to such installations should be avoided. This is especially true since the purpose of the monitoring system might be to measure the parameters of such cellular systems, which becomes impossible in the presence of a significant interferer.

Other man-made noise sources such as X-ray and diathermy machines, high-voltage power generation and distribution facilities, welding and heavy industrial fabrication processes, street lighting, heavy concentrations of vehicular traffic, and even large areas of residential buildings may create significant levels that may override wanted radio-frequency signals. In addition to direct radiation, noise from these sources may be conducted over power distribution lines to cause interference to areas at considerably greater distances than those affected by direct radiation.

Once a suitable location has been chosen from the standpoint of noise interference criteria, the influence of the terrain on reception should be examined. This is particularly important since the monitoring antennas are usually co-sited with a DF antenna. For the latter, it is important that the terrain be flat, free of discontinuities, and have an uninterrupted view in all directions in order to avoid errors in the azimuth of arrival of the radio waves. The siting of monitoring stations, and of DFs, is dealt with in §§ 2.5 and 5.7. However, it is true that except for limited, special, monitoring purposes, a good DF site is also a good location for monitoring antennas.

An effect which should be considered when choosing a site at which a number of different antennas are to be installed at the same location, is the interaction which will occur between them and with other nearby metallic structures such as antenna masts, mast guys, fences, metallic tubes, stairs and other metallic structures.

The interaction among multiple antennas at a site will be most significant for similar types of antennas either designed for the same frequency range or which attain near-resonance at the same frequency. For instance, it is recommended that two rhombic antennas should not be closer than about 10 wavelengths when one is in the lobe of the other at the receiving frequencies in use. For minimum interference between antennas of different types, it is recommended that maximum differences be provided in at least two of the general categories of space, frequency and polarization.

In addition to other antennas, surrounding metallic structures situated at distances less than several wavelengths from an antenna may unacceptably deform antenna characteristics such as elevation, azimuth antenna patterns and matching with feeders, relative to those in isolated conditions. Errors in the measurement of emission parameters, arising from such influence, can considerably exceed specified error tolerances indicated in Chapter 5.

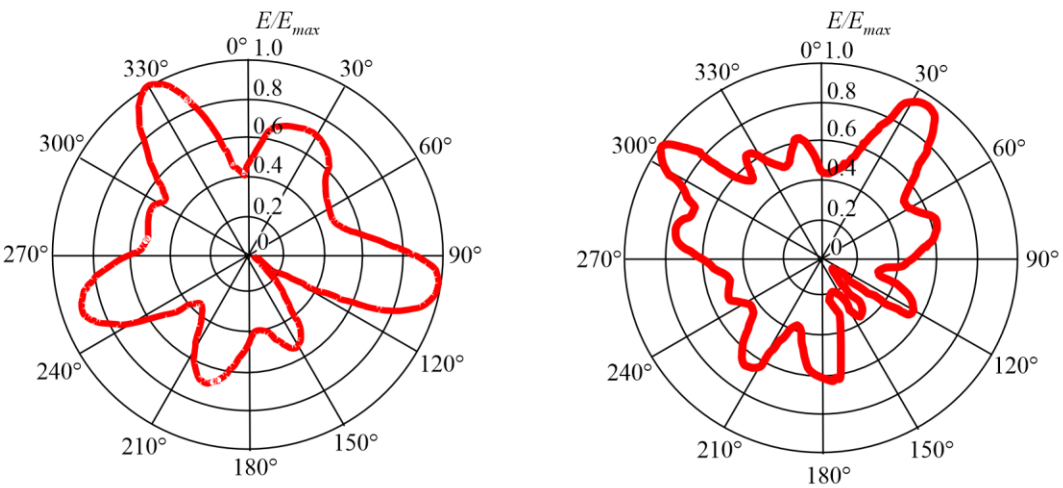
The quantitative determination of the influence of other antennas and metallic structures can be calculated with computer software [Kharchenko and Fomintsev, 2001], [Tanner and Andreasen, 1967], [Harrington, 1968], and [Thiele, 1973]. Metallic structures and other antennas within several wavelengths (usually from 4 to 8 wavelengths) from an antenna under consideration are modelled by wire structures, preserving the geometrical proportions of the structures. Then with the help of a method of moments computer program, the distribution of currents within all elements of wire structures are calculated; this electrodynamics model of the antenna and its surroundings allows the true characteristics of the antenna to be determined in the presence of scattering, reradiation and resonances produced by nearby metallic structures.

As an example [Kharchenko and Fomintsev, 2001] of the use of the given technique, Fig. 3-31 shows the calculated azimuth pattern of a 30-80 MHz omnidirectional disk-cone umbrella-type antenna in the presence of significant surrounding metallic structures. These structures include other similar antennas for the same frequency range and two disk-cone umbrella-type antennas for the range 80-100 MHz. There are also several rod communication antennas, a metal fence and some other metallic objects.

As is clearly seen from Fig. 3-31, surrounding antennas and other metallic structures convert an omnidirectional pattern such as illustrated in Fig. 3-28 to a directional one. Moreover, the variations in the patterns vary considerably with frequency, reaching differences of 20 dB due to non-linearity. This variation highly complicates the ability to obtain correct measurements from the antenna.

FIGURE 3-31

Actual azimuth pattern of omnidirectional 30-80 MHz antenna



E: field strength

a) $F = 40$ MHz b) $F = 60$ MHz

HDB-23-3-31

Some specific recommendations on the placement of antenna relative to the monitoring buildings and to one another are for:

HF loop antenna arrays. These should be at least 100 m from the array-receiving building to prevent distortion of radiation patterns by the receiving building.

MF/HF wideband arrays. These should not be located too far from the building (≈ 100 to 200 m). Enough spacing should be obtained to prevent shadowing of the antenna by buildings, but not so great as to introduce significant losses in the feed line. Coaxial line is recommended, since these antennas are wideband units with closely controlled impedance characteristics and somewhat lower gain than resonant types.

Transmitting and receiving antennas. Maximum separation should be maintained between antennas that are used for transmission and antennas used for reception, so as to minimize the overloading of receivers by signals generated by local transmitters. Care should be taken to locate transmitting antennas so that their main lobe and side-lobes do not directly illuminate antennas used only for receiving purposes.

DF antennas. If DF equipment is to be installed at the monitoring station, the possible effect of reradiated components from the receiving antennas should be considered in regard to their effect in introducing errors in the DF equipment (see §§ 2.3.4.3 and 5.7).

Active antennas. Since mutual coupling between active antennas, as well as mutual coupling between them and other structures, is reduced to a minimum, active antennas may be installed closer together than passive antennas. Active antennas can be disturbed by high-power radio transmitters, and this needs to be taken into account when siting those antennas.

VHF/UHF antennas (above 30 MHz). These should be located high on towers near the receiving building to minimize losses in the coaxial cable, to maximize LoS coverage area. For a 20 km LoS radius, a 24 m tower is required. A 48 m tower would provide LoS coverage out to about 30 km.

Antennas for frequencies above 1 000 MHz. These should be located where a clear LoS is guaranteed (e.g. on a building, tower or mountain), especially for terrestrial monitoring. The receiving systems should be installed close to the antenna to avoid high losses in the coaxial cable.

3.3.7 Transmission lines and distribution systems

3.3.7.1 Transmission lines

Transmission lines at monitoring stations conduct the received power from the antenna to the receiver.

Among the various types of transmission lines, the preferred solution at monitoring stations is the coaxial transmission line. Its impedance is uniform provided the dimensions of the various parts including the connectors are adequately controlled. Signals on good coaxial cables are not severely affected by the presence of other objects. Coaxial cables are manufactured in a wide variety of sizes and materials. Properties of the available coaxial cables are many and varied, and cover a wide price range. There are a number of manuals available, particularly from cable manufacturers, which list individual coaxial cable properties. It is important to use double-shield braid or solid outer conductor type coaxial cable.

A 3 dB total attenuation may be quite acceptable for a receiving transmission line. The use of an integrated receiver at the antenna base avoids long cable runs, reduces insertion loss and eliminates any need for an LNA in a switching unit.

3.3.7.2 Distribution systems

Once the energy received by a particular antenna has been conducted to a point inside the monitoring building, there is usually a requirement to distribute this energy to a variety of receiving positions. The distribution system should take into account the final use that is to be made of each output so that the optimization of results can be obtained. In general, the level of the signal should be maintained as high as possible, so that undue sensitivity is not required of receiving equipment. Also, the quality of the signal (S/N) should be maintained, or the degradation kept as low as possible, so that the advantages of high gain antennas and low-loss distribution cables are not compromised.

Receivers which are simply connected in parallel across a transmission line will degrade the monitoring system performance because of e.g., standing waves, undefined power splitting and local oscillator reradiation. This method is not recommended. Instead, matching and signal splitting should be used.

Distribution systems generally include an antenna switch and antenna duplexer. State-of-the-art technology is used to combine the two to achieve remote control via network.

In a receiving system, the equipment which distributes a signal from one antenna to a multi-channel receiver or multiple receivers is known as a duplexer. An antenna duplexer may be comprised of multiple duplexers and may include single filters that isolate different signal paths; an LNA is used to compensate for the attenuation and the controlling circuit.

An antenna switch selects from several antenna inputs a wanted input signal for one receiver. Like antenna duplexers, an antenna switch consists of different components for different frequency bands because of the frequency limitation of individual components; insulation design is necessary between these components. LNA are sometimes used to compensate for the attenuation of components.

An RF signal distribution system is used to distribute signals from different antennas to different receivers. Signals from any antenna are available to any one of the receivers; any input signal can be delivered to any output of the distribution system.

Despite the burgeoning development of digital signal processing technology in signal detection, demodulation and DF, analogue technologies are still necessary in signal distribution. A good distribution system should be optimized for performance in such areas as sensitivity, dynamic range, switch of RF signal, capability of distribution, and isolation between channels. Specifications of a distribution system should include the following major parameters:

- frequency range;
- insertion loss;
- isolation;
- dynamic range;
- third order intermodulation product (IP3);
- noise figure.

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Related ITU-R Recommendations

NOTE – In every case the latest edition of the referred Recommendations is encouraged to be used.

Recommendation ITU-R F.162 – *Use of directional transmitting antennas in the fixed service operating in bands below about 30 MHz*

Recommendation ITU-R BS.705 – *HF transmitting and receiving antennas characteristics and diagrams*

3.4 Monitoring receivers

3.4.1 General considerations

The performance of a monitoring station is directly related to the quality of the station equipment including the antennas, receivers, radio DF and processors. Antennas, DF and processing equipment are discussed in §§ 3.3, 3.5 and 3.7. An in-depth study of receivers would require a dedicated book, so only an overview of the composition of receivers, definition of the main features and operating precautions is provided here.

The function of a receiver is to select a radio signal from all the signals intercepted by the antenna to which it is connected, and to reproduce at the receiver output the information transmitted by the radio signal or its characteristics. In the past, most receivers have used entirely analogue circuitry, but most modern receivers are "hybrid" in architecture with Analogue RF "front-ends" and Digital "back-ends". The RF portion still uses classical superheterodyne circuit blocks (that are constantly updated as technology improves) and the Digital portion uses digital signal processing (DSP) techniques to implement many IF and Baseband receiver functions previously performed by analogue circuits: from simply digitizing the detector output to digitizing and downconverting full IF and baseband spectral segments, including digital demodulation, such as performed by "software-defined radio" systems.

Due to technological improvements, modern receivers are becoming more and more compact. Miniaturization of high stability oscillators; greater use of Monolithic Microwave Integrated Circuit (MMIC) technologies (Si, GaAs, SiGe, Silicon-On-Insulator, and many other semiconductor materials) for switches, amplifiers, variable attenuators, PLLs, filters, mixers, etc; and advanced packaging techniques allow the analogue portion of a receiver to become smaller and higher performing. Greater bandwidth, sensitivity, linearity and other performance parameters have all improved. The digital backend has also become more powerful and compact, due to improvements in analogue to digital converters (present performance exceeding 40GSa/sec), memory capacity and speed (SRAM and DRAM), Processors (multi-core, DSP). 1, 10, 100GbE and other high-speed interfaces are available for real-time data transfers, and non-volatile memory in SSDs spanning tens of TBytes can be used for recording and processing of these data streams. While size, weight and performance of today's systems have seen huge improvements, power consumption and costs have seen commensurate increases, though these see constant improvement as well.

It should be noted that while fully-digital receivers are viable for Direct-RF conversions, due to the stringent requirements of Spectrum Monitoring tasks, the performance afforded by the analogue RF front-end (bandwidth, sensitivity, distortion, signal isolation, etc.) continues to mandate hybrid architectures, especially

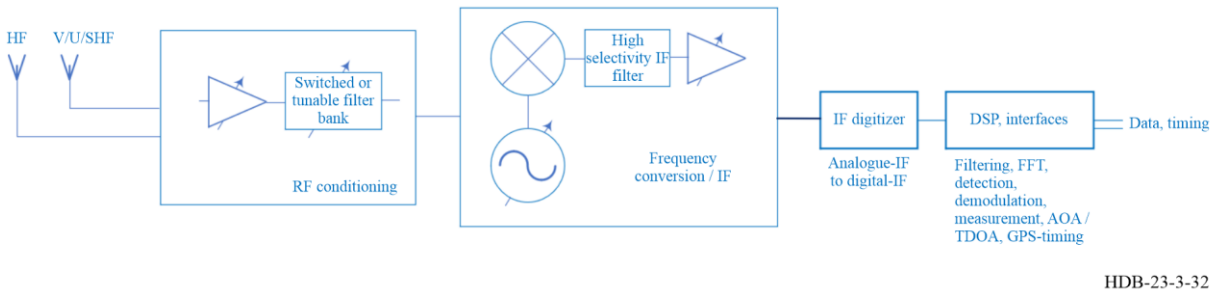
at higher frequencies. This is discussed in more detail below with a split emphasis between the RF / Analogue Front-end and the Digital Back-end.

3.4.2 RF Front-end / Tuner

The block diagram in Fig. 3-32 shows a functional implementation of a hybrid receiver with a superheterodyne front-end. Depending on the requisite tuning range of the receiver, there may be more than a single frequency conversion involved (often two) and this is implemented through judicious frequency planning.

FIGURE 3-32

Typical block diagram of a hybrid receiver front-end



An input amplitude conditioning block (variable or switched LNA/Attenuator) establishes system sensitivity and / or distortion performance (described in more detail below). The input filter (or Preselector), is typically a bank of suboctave fixed or tracking filters, and allows for the reception of the desired signals and attenuates those which are out-of-band. This block greatly reduces second-order IMD effects and enhances IF and Image rejection as well as reduces LO radiation (to reduce antenna emissions) from the LO driving the mixers. The Preselector filters' passbands are selected based on known spectrum usage as well as the need to mitigate frequency mixing products (mRF × nLO) that arise due to the multiplicative nature of the frequency converters used.

The Frequency Converter (or mixer) generates up- or down-converted intermediate-frequency (IF) products that are subsequently filtered (by analogue or digital means) with sharp, selective stopbands to provide a high-fidelity representation of the signal of interest. There may often be more than a single IF frequency incorporated in the implementation of a low-spurious conversion plan. The Local Oscillator (LO) driving the frequency converters are wideband, low-noise, agile frequency synthesizers. These are an integral part of the tuner frequency planning and their fundamental and harmonic components, phase noise, spurious products, and frequency stability contribute to the signal fidelity of the RF front-end.

IF amplitude levelling to ensure linear operation as well as providing a nominal integrated power window to the Digitizing section is important. RF and IF amplitude conditioning is of paramount importance for the monitoring task as the received spectrum can have very high-level signals (e.g. collocated broadcast transmissions) and very low-level signals (e.g. very distant handsets).

The designer of a monitoring receiver should therefore pay attention to the interaction of transmissions at high- and low-power levels falling within the IF passband and, most especially, high-level interfering signals falling inside and outside of both Preselector and IF filter bands. It is generally these interfering signals that are responsible for spurious intermodulation products that often overlay low level signals. The intermodulation between two signals occurs when such signals go through a non-linear circuit as described in § 7.5. The quality of a receiver, from the intermodulation point of view, is characterized by the value of its second- and third-order intercept points, which should be as high as possible. Additionally, if the levels of the interferers are high enough, blocking action due to saturation effects in the RF or IF chains can prevent the wanted signal from realizing the anticipated receiver gain.

To mitigate these effects, it is necessary that all components in the RF front-end have sufficient linearity and system gain management to support the requisite dynamic range needed for the monitoring task. Monitoring receivers usually contain switchable or programmable-gain preamplifiers. These allow the receiver to operate

either in high sensitivity mode (with the preamplifier in the "on" mode) or high linearity/low distortion mode (with the preamplifier in the "off" mode). Receivers may also require an external attenuator (or even have integrated switched attenuation) to enable monitoring while exposed to extremely high-level emissions (e.g. a collocated tower transmitter) that could otherwise cause overload, system distortion and blocking.

The RF amplifier's gain and noise figure partly determine the receiver sensitivity. Receiver sensitivity is limited by the noise generated at its input circuits (in particular by the RF amplifier and sometimes double-sideband mixer noise) as well as the passive losses before the LNA. The sensitivity is also expressed by the noise figure in Tables 3-3 and 3-4, which should be as low as possible. The relationship between sensitivity and noise factor, for the same receiver, involves the receiver passband.

When a receiver is connected to an antenna, in addition to its own internally generated noise, naturally occurring noise is added, such as atmospheric, galactic and solar noise, as well as noise from industrial sources, radiation from electronic equipment, and radiation from transmitters generally. The designer of a monitoring station has, therefore, to select the receiver from the standpoint of its sensitivity, according to the noise levels measured.

It is also important that a monitoring receiver does not produce detectable noise or interference of its own. The LO's that drive the frequency converters are generally at a high-level. Fortunately, these mixers will provide some LO suppression. Further, front-end amplifier reverse isolation and Preselector rejection also contribute to LO rejection and together, these attenuate the local oscillator signal level before it reaches the antenna to generate spurious radio emissions.

Other characteristics should also be specified or investigated, such as:

– bandwidths and selectivity of intermediate frequency filters;
– types of demodulation supported (which can be affected by phase noise);
– effectiveness of the automatic gain control (in presence of in-band / out-of-band interferers);
– effectiveness of the automatic tuning system;
– frequency accuracy, timing and group delay stability to ensure the system can establish precise temporal and geo-parametrics for DF;
– calibration requirements (e.g. interval, time needed, and location of service) to ensure accurate frequency and amplitude characterizations;
– changes to performance characteristics resulting from variations in the temperature; and
– effects of mechanical perturbations such as shock / vibration

Normally two types of receivers are used to cover the frequency range from 9 kHz to 6 000 MHz, one for frequencies up to 30 MHz and the other for 20 MHz – 6 000 MHz. Because antenna bands are similarly partitioned between different physical antennas, the RF Tuner must often accommodate different antenna ports for these different bands. It is also the case that with modern receivers, the cumulative LF/MF/HF bands can be directly digitized. Monitoring systems may have partitioned, suboctave bands for these ranges as well, but due to the physical components that comprise filters at these low frequencies, such accommodations can add greatly to the size, weight and cost of a monitoring receiver. So more compact solutions can entail a reduced filter set for these low frequencies. Additionally, if an extended frequency range (e.g. up to 40 GHz) is to be covered, supplemental down-conversion hardware may be required.

All the qualities expected of receivers for use at a main receiving station are required of monitoring receivers with the addition of good frequency setting accuracy (better than or equal to 1ppb is possible with long-term frequency stable sources using GPS-disciplining) and rapid tuning.

3.4.3 Digital Processing Sections

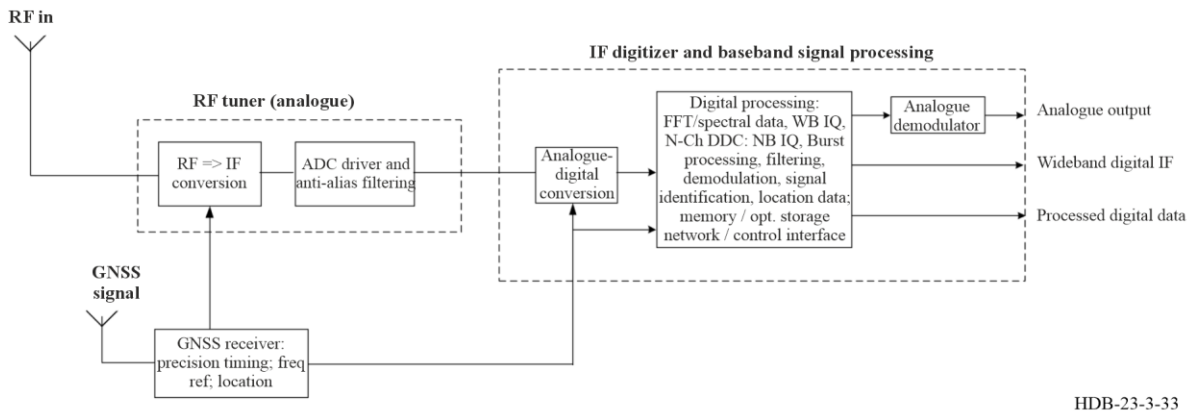
The advent of high-speed, low-cost digital signal processing (DSP) chips and high dynamic range analogue to digital (A/D) converters has made possible the design of high-performance digital receivers. This digital processing provides improved performance in frequency conversion; filtering and demodulation, which leads to increased selectivity, stability and automatic gain control. Additionally, functions such as adaptive interference cancellation, and speech enhancement and recognition not found in analogue processing may be available in digital receivers. These functions are very important when attempting to sort and identify specific

signals in a congested signal environment. A benefit of digital processing is in performance, repeatability, and stability over time and temperature. Improved adaptability is another benefit, an example of which is the ability to recognize and identify complex modulation formats commonly used in cellular and high-performance control links. IF bandwidth adjustability, demodulation modes, and other functions can be performed in a DSP-based receiver by software change versus costly hardware modifications. Filters can be synthesized by digital processing to provide extremely sharp filter shape factors, while maintaining very flat amplitude and linear phase response over the desired pass band. This process minimizes signal distortion usually introduced by equivalently narrowband analogue filters. It is also possible to generate very narrow (less than 50 Hz) RBW filters allowing direct measurement of transmitter carrier spurious components such as power line related hum. It is important to remember that a digital filter operating on the wideband digitized IF is not a replacement for analogue pre-selection filtering in in the RF front end.

The basic elements of the Digital section include: IF digitizer, signal processor, and analogue signal reconstruction modules, all shown in Fig. 3-33 with the RF tuner front-end (with appropriate analogue anti-aliasing filtering) and precision GNSS circuits.

FIGURE 3-33

Digital and baseband processing functions following tuner



The first major processing step is the conversion of the IF signal to digital form. The IF digitizer utilizes an Analogue-to-Digital Converter (ADC) to digitize the analogue IF. The ADC usually has very high resolution (14-16 bits), high sampling rates based on the bandwidth of the IF, and high linearity (70 dB SFDR or higher) with high-speed interfaces for subsequent DSP. The resulting digitized signal is used by the signal processor to perform such functions as filtering, fine tuning and demodulation. Digital output from the module is then made available for further processing and/or recording. The analogue signal reconstruction module converts the digital outputs to analogue for operator monitoring or further processing.

Many tuner characteristics listed in § 3.4.2 apply also to this digital section. Additionally, receivers performing spectrum monitoring tasks according to ITU-R Recommendations should provide the following functions:

– scan of predefined frequency ranges;
– memory scan of several hundred channels;
– Digital downconverters (DDC's)
– audio monitoring using FM, AM, CW and SSB demodulation;
– signal identification using modulation recognition features;
– storage of measured values for a later use or download.

Processing these different functions for the various types of signals, with optimum *S*/*N*, requires a large number of IF bandwidth settings, and this is well-suited to the programmability of DSPs.

DDC's enable selected signals to be mixed down from the wideband ADC data to baseband for further processing (measurement of modulation-parameters, demodulation, decoding, identification). By using a bank

of DDC's in parallel (implemented e.g. in FPGA, DSP or ASIC) many signals can be mixed down and analysed simultaneously. Every DDC can be tuned in the frequency range covered by the wideband IF and works as a virtual receiver. DDCs can be especially useful for processing signals that were recorded within a digital wideband IF by replaying the digital IF back to the wideband receiver and using the DDCs to select the signals of interest for processing.

This processing technique makes it possible to detect and analyse short-duration transmissions such as frequency hopping signals. The bursts of hopping transmitters are received with the wideband receiver (live or replayed) and detected with an automatic burst detection algorithm. By using DDCs, the individual hops are mixed down to baseband and analysed (exact hop length, bandwidth, modulation-parameters). An evaluation process investigating the measured information of all detected bursts determines the different types of bursts, the different hop rates, patterns, and hop-sets (frequencies) of the transmitters. This statistical analysis provides information about hopper scenarios like the number of active hopping transmitters and the types of communication methods used.

Monitoring receivers may include an integrated display and built-in control unit, or embedded processor with software that provides a "Virtual Control Panel" accessible by a remote interface such as a LAN (Ethernet). Also, monitoring receiver operational modes should support the most common ITU spectrum monitoring and measurement tasks described in Chapters 1 and 5.

Monitoring receivers may be operated independently but are often integrated into a complete measurement and processing system as described in § 3.7. The receivers include a number of interfaces, such as: Digital IF output, I/Q-based output for DF, wideband IF output for external panoramic display, output for external loudspeaker and headphone socket. Provision should also be made for the connection of additional equipment / interfaces, i.e. computers, recording drives, other human-machine interfaces (HMI), GNSS antenna, cooling systems, backup power.

3.4.4 Frequency reference sources for receivers

There are multiple frequency sources required for the monitoring receiver. The local oscillators require high-frequency, broadband, low-phase noise, agile synthesizers to scan the RF with high-fidelity to generate the IF. The digitizer / DSP also require high precision clocks that are often derived from the same time base as the Tuner. A low-noise frequency reference with excellent short-term stability is often locked to a precision GNSS source to provide ultra-long-term stability. The accuracy required for a frequency reference used with modern receiving systems is becoming more and more stringent and is the reason why the synthesizer should have the highest possible precision and stability. Consequently, most monitoring stations have a precision GNSS time/frequency reference and associated frequency synthesizer(s) to cover a wide range of applications. For additional information on GNSS, refer to § 7.1.

3.4.5 Key performance characteristics of monitoring receivers

Noise Figure (NF)

The noise figure is one of the main specifications of a monitoring receiver. The noise figure is closely tied to the sensitivity of the monitoring receiver.

The noise figure of a monitoring receiver is the factor by which the noise power delivered by the monitoring receiver increases when a reference noise is applied to the input. The noise figure is referenced to the input of the monitoring receiver and is measured at the output.

The noise figure is measured under normal operating conditions over the entire temperature range indicated in the data sheet at the most sensitive setting of the receiver (without attenuation and with built-in preamplifier on).

In accordance with Recommendation ITU-R SM.1838, a maximum value for the noise figure should be specified and published by the manufacturer in the data sheet over the receiver's whole operating range.

Third Order Intercept Point (IP_3)

The third order intercept point is an important performance measure that specifies the amount of distortion superimposed on the desired signal due to the intermodulation distortion (IMD) of two interfering signals (or even the IMD of a single emitter with a broadband spectrum the IMD of which can overlap a lower-level,

adjacent Signal-of-Interest (SOI)). Third order intercept point is a hypothetical point where the power of third-order products is equal to the power of the generating source. The highest IP_3 is not necessarily at the most sensitive setting of the receiver (lowest NF). The third order intermodulation is measured under normal operating conditions over the entire temperature range indicated in the data sheet in accordance with Recommendation ITU-R SM.1837. Condition 1 discussed in this Recommendation is preferable because of the characterization of performance through the digitizer.

Second Order Intercept Point (IP_2)

When two or more strong out-of-band (OOB) or in-band signals pass through non-linear components in the monitoring receiver, distortion products are generated at the sum and difference frequencies and are referred to as second order distortion or IP_2 products. Unlike IP_3 products (which fall spectrally adjacent to the two input signals), IP_2 products can be more displaced from the two input signals that originate them. Because a monitoring receiver will typically have suboctave preselectors, the two input signals and their resulting IP_2 products will not simultaneously fall within one preselector band. For example, input frequencies at 222 MHz (e.g. DAB+ broadcast station) and 666 MHz (e.g. DVB-T2 transmitter) will result in second order distortion products at 444 MHz and 888 MHz. If the monitoring receiver is tuned to 444 MHz (e.g. public mobile radio (PMR) service) to locate unwanted emissions and the preselector filter covers 300 MHz to 500 MHz (allowing passage of 444 MHz, while at the same time stopband filtering 222 MHz and 666 MHz), then the generation of the second order distortion product at 444 MHz will be greatly suppressed. In this case, the sub-octave preselector helps to lower the unwanted 2nd order intermodulation product below the signal of interest. And, like IP_3, this parameter should not be specified at maximum gain, but at a prescribed gain control setting.

Dynamic Range

The useable dynamic range of a receiver can assume a myriad of definitions and dependencies and is described briefly in § 3.4.6.

IF Filter Properties

The bandwidth of the IF filter of a monitoring receiver in ITU is defined as the −6 dB bandwidth. The shape factor is defined as the ratio of the −60 dB and −6 dB bandwidth ($BW_{IF\text{-}60}/BW_{IF\text{-}6}$, so an ideal rectangular filter has a shape factor of 1). When another bandwidth is used, the shape factor is defined as the ratio of this bandwidth and the −60 dB bandwidth.

Instantaneous bandwidth (IBW)

Instantaneous bandwidth is the maximum continuous range of radio frequencies that a receiver can receive and process simultaneously. A wider IBW affords faster spectral processing when the monitoring receiver or spectrum analyser is sweeping because fewer separate steps or captures are required to cover a given spectrum. A narrower IBW generally may afford better sensitivity and noise performance. A wider IBW does require higher dynamic range components for a given sensitivity since more of the spectrum (and thus more noise power) is included in the broader bandwidth.

Phase noise

The phase noise performance of a receiver directly impacts the ability to resolve closely spaced signals of different amplitudes and to perform accurate demodulation. Phase noise in a receiver phase modulates received signals increasing their bandwidth. Two adjacent signals that may not have overlapping spectrums at the input to the receiver may interfere with each other in the receiver once modulated by the receiver phase noise.

Phase noise is multiplicative and therefore is specified as a noise density relative to a carrier (dBc/Hz), the larger the signal, the greater the phase noise power. The greatest impact of phase noise is on closely spaced signals of unequal power.

The larger signal will have greater power in the phase noise sidebands and therefore have greater impact on the detection or demodulation of the weaker adjacent signal than the other way around. For large signals, phase noise limits the receiver's dynamic range.

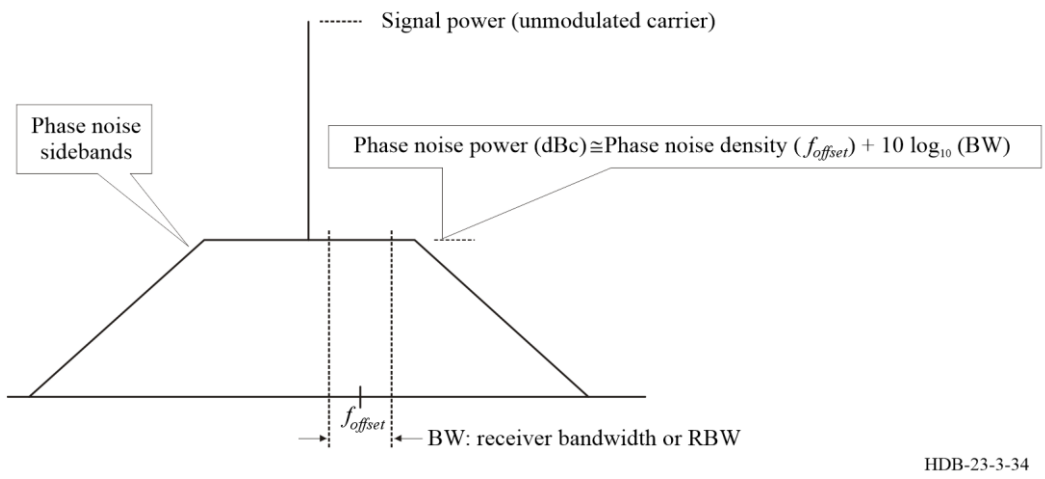
Phase noise density is usually specified at fixed frequency offsets such as 10 kHz or 100 kHz. The phase noise density is generally greatest at small frequency offsets. For this reason, the phase noise requirement is largely determined by the types of signals to be monitored. Phase noise requirements will be more stringent for

narrowband signals than for wideband signals, so receiver specifications will be driven primarily by the narrowest carrier (or subcarrier) to be monitored.

With the assumption that the phase noise spectrum is relatively flat across the measurement bandwidth (BW), the dynamic range near a large signal can be estimated as illustrated in Fig. 3-34. So, for the aforementioned 10 kHz frequency offset between a high-level carrier and a lower-level 1 kHz wide signal of interest, a carrier phase noise of −100 dBc/Hz would result in a −70 dBc noise power contribution that overlays the lower-level SOI, and result in a 70 dB dynamic range.

FIGURE 3-34

Estimation of dynamic range and phase noise power



The frequency offset and required bandwidths affect the receiver's phase noise power requirement. For example, HF applications have narrower bandwidth requirements whereas UHF applications have wider bandwidth requirements. Therefore, synthesizers, or local oscillators (LOs) for HF monitoring receivers should have commensurately lower phase noise than those for UHF applications. And for cases where the HF band is directly digitized, the phase noise performance of the digitized signals should be commensurate with the phase noise of the sampling clock as appropriately amended by the SOI frequency displacement from the clock frequency. For example, if the ADC uses a 200 MHz clock, and the SOI is centred at 25 MHz, it should be expected that the phase noise measurement of the digitized SOI can be no better than that of the sample clock less 20*Log(8) dB or (16) dB at any given offset.

3.4.6 Specifications for typical monitoring receivers

A monitoring receiver should generally meet the specifications for VLF/LF/HF and VHF/UHF receivers that are given in Tables 3-3 and 3-4. One should also consider these specifications as a general guideline to select equipment that is able to provide good performance and reliability for the tasks required by a monitoring system. For certain applications, simpler receiver equipment might be suitable.

Certain receiver parameters given in Tables 3-3 and 3-4, such as third order intercept, noise figure, and filter parameters, are so important and have such a direct influence on the suitability of a receiver for monitoring tasks, that their specification and measurement procedures are defined by ITU-R Recommendations. Measurement results strongly depend on the test procedures used, and standardized test procedures allow easier and more objective comparison of products from different manufacturers. Scanning speed, discussed in Recommendation ITU-R SM.1839, is very dependent on the intent of the measurement; for example, the required receiver scanning speed to detect the presence of a single-event signal burst is much faster than measuring parameters or characteristics of a persistent signal.

Because of the relevance of NF and IP3 and their impact on receiver dynamic range, it is especially important that a minimum performance is required from the field of qualified manufacturers. Since the signal environment is always becoming more complex with emitters occupying broader signal bandwidths and wider breadths of signal power levels, it behoves operators to have even better than these minimum performance levels. To put into perspective, 3 dB improvements in sensitivity can result in 40% further detections; and 3 dB improvement in IP3 can result in 100% increase in interferer level whilst maintaining dynamic range.

The specifications in Tables 3-3 and 3-4 represent the performance of a good quality commercial monitoring receiver suitable for use in ITU related monitoring tasks. The tables describe specifications that are met by manufacturers of typical monitoring receivers. These are not to be considered as 'minimum', nor 'best achievable'. Administrations should consider their own needs when specifying equipment performance, using the table as a guide. The performance of a receiver intended for different applications (other than a general-purpose monitoring receiver) may emphasize improvement in some specifications and relaxation in others.

The tables below contain only those specifications that are of particular relevance with respect to the intended use of the receivers. In the following cases, a table field may be left empty:

– The parameter is not important for the typical deployment of the receiver.

– Variation of typical values for the parameter are so high that it is not possible to state a general figure.

Transportable stations have a large variety of designs and applications. They could range from simple, tripod-mounted receivers to fully equipped sheltered installations. Depending on the design and expectations of a transportable station, the values from Tables 3-3 and 3-4 apply. The term "mobile monitoring station" in Table 3-3 refers essentially to general-purpose vans. Nonetheless, § 3.2.2 includes a variety of mobile platforms that may be used in dedicated scenarios. As such, Tables 3-3 and 3-4 should support the design and selection process for the individual station.

Receiver sensitivity, linearity, and usable dynamic range

Certain parameters in Tables 3-3 and 3-4 become more or less important in practice. This is especially true for the sensitivity, which is expressed as the noise figure (NF) or displayed average noise level (DANL), and the linearity or immunity against strong signals, which is best expressed as the IP_3. In practice, the maximum usable RF level is limited by the point where the intermodulation (IM) signals become visible above the DANL, because then it is difficult for the user to distinguish between real and fake RF signals. At this point, the 2nd order IM products are much lower in level, so that the IP_2 value in the table is of even less practical importance.

The difference between DANL and the maximum input level of the receiver where still no IM products are visible is referred to as the usable dynamic range. This range is of highest practical importance in most standard RF environments and measurement tasks.

Impact of the RF environment on receiver configuration

Manufacturers can optimize their receivers with a plethora of configurations, often using different gain modes with settings that are optimized for different input signal environments: from low-level input signals that require high receiver sensitivity to high input signal levels requiring minimal distortion. For all modes, there is a compromise of highest possible sensitivity (lowest NF) with simultaneously the highest possible linearity (IP_3) together with the best possible suppression of the IP_2 products. Receiver configuration is always a compromise between sensitivity and immunity against strong signals.

At exposed locations (e.g. Monitoring Stations on high towers), especially in urban areas, very high field strengths from nearby broadcast and/or cellular network transmitters (even in excess of the values calculated in Recommendation ITU-R SM.575) can be expected. In this situation, the immunity against strong signals is more important than sensitivity. Receiver configurations providing high IP_3 provide the requisite linearity to handle the higher field strengths and are generally accompanied by a reduction of receiver sensitivity (higher noise figure). However, the degradation in sensitivity should still allow simultaneous processing of lower-level signals within the receiver's usable dynamic range. Sub-octave preselection and high IP_2 can mitigate effects of higher level, far-from-tuned frequency signals; and steep IF filtering can mitigate effects of higher-level, close-to-tuned-frequency signals.

When installed in remote, rural areas, with no strong transmitters within several kilometres distance or when nearby emissions are lower in power (e.g. from handsets, cell phones…) – in a low field strength scenario – a low noise figure becomes the more important parameter. For these scenarios, the monitoring receiver needs to have sufficient sensitivity and low residual spurious to be able to resolve the lower-level signals. IP_3 and IP_2 generally suffer when receiver gain is ratcheted up to realize best Noise Figure / sensitivity but should still be sufficient to allow simultaneous processing of higher signal levels within the receiver's dynamic range. The same is true for receivers intended for use in mobile monitoring stations because there is often the possibility to move away from the strongest transmitters, whereas sensitivity is of most importance to compensate for the limited antenna height.

It must be noted that every manufacturer could configure its receiver in different ways for different signal scenarios – but for processing of practical signal levels (in a congested signal environment) the receiver should meet the parameters stated in Tables 3-3 and 3-4. The parameters, such as NF and IP_3, in these tables are measured in different receiver settings.

Depending on the receiver architecture, these receiver settings can differ from extreme hardware configurations, such as excessive low-noise front-end gain or attenuation, that can result in extremely low NF and poor IP_3 or very high IP_3 and poor NF, respectively. Recommendations ITU-R SM.1837 and ITU-R SM.1838 call out for zero attenuation conditions. But such a zero-attenuation condition (for example with ITU-R SM.1838 noise figure) can result in the case of good NF and poor IP_3. A rebalance of settings can be appropriate to yield the practical values reflected in Table 3-3.

Therefore, among other aspects, the decision for or against a particular receiver will also depend on the expected RF environment in which it will be operated. A robust discussion on planning spectrum monitoring stations and networks for differing environments and conditions can be found in Chapter 2 and Report ITU-R SM.2356.

TABLE 3-3

Specifications for typical monitoring receivers to be used in fixed and mobile monitoring stations

Parameters	**VLF/LF/MF/HF**	**Extended VHF/UHF (6)**
Frequency range	9 kHz to 30 MHz	20 MHz to 6 000 MHz (4)
Tuning resolution	≤ 1 Hz	≤ 10 Hz
Tuning error	≤ 1 ppm, or ≤ 0.01 ppm using global positioning by satellite for external reference	≤ 0.1 ppm, or ≤ 0.01 ppm using global positioning by satellite for external reference
Synthesizer settling time	≤ 10 ms	≤ 1 ms
Amplitude accuracy (at 25 °C)	≤ ±2 dB	≤ ±3 dB
Input (antenna input) VSWR	50 Ω, nominal ≤ 3	50 Ω, nominal ≤ 2.5
RF attenuation range	0 to 25 dB, in steps of 5 dB	0 to 40 dB, in steps of 1 dB
RF preselection	Set of suboctave band filters or tracking filter	Set of suboctave band filters or tracking filter
2nd order intercept (with gain control)	≥ 60 dBm (> 3 MHz)	≥ 40 dBm
3rd order intercept, receiver test "Condition 1" (1)	≥ 20 dBm (> 3 MHz)	≥ 10 dBm (20 MHz to 3 000 MHz) ≥ 12 dBm (3 000 MHz to 6 000 MHz)
Noise figure (2)	≤ 15 dB (> 2 MHz)	≤ 12 dB (20 MHz to 3 000 MHz) ≤ 15 dB (3 000 MHz to 6 000 MHz)

TABLE 3-3 (*end*)

Parameters	**VLF/LF/MF/HF**	**Extended VHF/UHF** [(6)]
LO-phase noise in 10 kHz offset	≤ −120 dBc/Hz	≤ −100 dBc/Hz (20 MHz to 3 000 MHz) ≤ −95 dBc/Hz (3 000 MHz to 6 000 MHz)
IF / image rejection	≥ 80 dB	≥ 80 dB
Instantaneous bandwidth (IBW)	Up to 30 MHz	20 MHz/100 MHz[(5)]
IF bandwidths (−6 dB)	from 0.1 kHz to at least 100 kHz[(3)]	from 1 kHz to maximum IBW[(3)]
Selectivity 60 to 6 dB (shape factor)	2:1[(3)]	2:1[(3)]
Detection / demodulation modes	AM, FM, CW, LSB, USB	AM, FM, CW, LSB, USB
Measurement and display functions	Time gated measurement, Channel power measurement, I/Q recording and output, Spectrum display with persistence Spectrogram	Time gated measurement, Channel power measurement, I/Q recording and output Spectrum display with persistence Spectrogram
Outputs – IF	Digital IF output	Digital IF output
Audio	0 dBm, 600 Ω or digital streaming audio and ear-phone jack	0 dBm, 600 Ω or digital streaming audio and ear-phone jack
IF monitor	For external IF monitor, or digital data stream	For external IF monitor, or digital data stream
Support for additional functions	AOA, TDOA	AOA, TDOA
Remote control interface	Ethernet LAN or USB or SFP+	Ethernet LAN or USB or SFP+
Built-in user interface	Not required	Not required
Electromagnetic compatibility	IEC 61000-4-2, -3, -4 CISPR 11, group 1, class B	IEC 61000-4-2, -3, -4 CISPR 11, group 1, class B
Operating temperature range	0 to 45 °C	0 to 45 °C
Relative humidity	95% non-condensing	95% non-condensing
Vibration	IEC 60068-2-6 or MIL-STD-810	IEC 60068-2-6 or MIL-STD-810

(1) Measurement procedures according to Recommendation ITU-R SM.1837.

(2) Measurement procedures according to Recommendation ITU-R SM.1838. If an LNA is available, it needs to be switched ON for the measurement, as stated in the Recommendation.

(3) Measurement procedures according to Recommendation ITU-R SM.1836.

(4) For mobile stations, even higher frequencies than 6 GHz may be considered.

(5) For the purpose of monitoring wider signals such as 5G, 100 MHz may be considered. However, the parameters IP2, IP3 and level accuracy apply to bandwidths up to 20 MHz.

(6) While the ITU definitions for VHF and UHF are respectively 30 to 300 MHz and 300 to 3 000 MHz, the parameters in the Table are for typical monitoring receivers that are designed for the frequency range 20 MHz to 6 000 MHz.

TABLE 3-4

Specifications for typical portable monitoring receivers

Parameters	Extended VHF/UHF (5)	SHF
Frequency range Tuning resolution Tuning error	20 MHz to 6 000 MHz ≤ 10 Hz ≤ 1.0 ppm, or ≤ 0.01 ppm using global positioning by satellite for external reference	≥ 6 000 MHz ≤ 10 Hz ≤ 1.0 ppm, or ≤ 0.01 ppm using global positioning by satellite for external reference
Synthesizer settling time	≤ 1 ms	≤ 1 ms
Amplitude accuracy	≤ ±3 dB	≤ ±3 dB
Input (antenna input) VSWR	50 Ω, nominal ≤ 2.5	50 Ω, nominal ≤ 3
RF attenuation range	0-30 dB, in steps of 5 dB	0-30 dB, in steps of 5 dB
RF preselection	Set of suboctave band filters or tracking filter	Set of suboctave band filters or tracking filter
2nd order intercept (with gain control)	≥ 40 dBm	≥ 40 dBm
3rd order intercept, receiver test "Condition 1" (1)	≥ 10 dBm (20 MHz to 3 000 MHz) ≥ 12 dBm (3000 MHz to 6 000 MHz)	≥ 12 dBm
Noise figure (2)	≤ 13 dB (20 MHz to 3 000 MHz) ≤ 17 dB (3 000 MHz to 6 000 MHz)	≤ 20 dB (up to 8 000 MHz)
LO-phase noise in 10 kHz offset	≤ −95 dBc/Hz	≤ −95 dBc/Hz
IF / image rejection	≥ 70 dB	≥ 70 dB
Instantaneous bandwidth (IBW)	20 MHz / 100 MHz (4)	20 MHz / 100 MHz (4)
IF bandwidths (−6 dB) (3)	from 1 kHz to maximum IBW	from 1 kHz to maximum IBW
Selectivity 60 to 6 dB (shape factor)	2:1(3)	2:1(3)
Detection / demodulation modes	AM, FM, CW, LSB, USB	AM, FM, CW, LSB, USB
Measurement and display functions	Time gated measurement, Channel power measurement, I/Q recording and streaming, Spectrum display with persistence, Spectrogram	Time gated measurement, Channel power measurement, I/Q recording and streaming, Spectrum display with persistence, Spectrogram
Support for additional functions	AOA, TDOA	AOA, TDOA
Outputs – Audio	0 dBm, 600 Ω or digital streaming audio and ear-phone jack	0 dBm, 600 Ω or digital streaming audio and ear-phone jack
Remote control interface	Ethernet LAN, or USB	Ethernet LAN, or USB
Built-in user interface	Full colour display	Full colour display
Electromagnetic compatibility	IEC 61000-4-2, -3, -4 CISPR 11, group 1, class B	IEC 61000-4-2, -3, -4 CISPR 11, group 1, class B
Operating temperature range	−10 ° to +55 °C	−10 ° to +55 °C
Relative humidity	95% non-condensing	95% non-condensing
Ingress Protection Class	≥ IP51 in line with IEC 60529	≥ IP51 in line with IEC 60529
Vibration	IEC 60068-2-6 or MIL-STD-810	IEC 60068-2-6 or MIL-STD-810
Weight including battery	≤ 5 kg	≤ 5 kg
Battery life	≥ 2.5 hrs (6)	≥ 2.5 hrs (6)

Notes to Table 3-4:

(1) Measurement procedures according to Recommendation ITU-R SM.1837.

(2) Measurement procedures according to Recommendation ITU-R SM.1838.

(3) Measurement procedures according to Recommendation ITU-R SM.1836.

(4) For the purpose of monitoring wider signals such as 5G, 100 MHz may be considered. However, the parameters IP2 and, IP3 and level accuracy apply bandwidths of up to 20 MHz.

(5) While the ITU definitions for VHF and UHF are respectively 30 to 300 MHz and 300 to 3 000 MHz, the parameters in the Table are for typical monitoring receivers that are designed for the frequency range 20 MHz to 6 000 MHz.

(6) Using a hot-swappable battery if necessary.

References

ITU-R Publications

NOTE – In every case the latest edition of the referred Recommendations is encouraged to be used.

Recommendation ITU-R SM.1836 – *Test procedure for measuring the properties of the IF filter of radio monitoring receivers*

Recommendation ITU-R SM.1837 – *Test procedure for measuring the 3rd order intercept point (IP3) level of radio monitoring receivers*

Recommendation ITU-R SM.1838 – *Test procedure for measuring the noise figure of radio monitoring receivers*

Recommendation ITU-R SM.1839 – *Test procedure for measuring the scanning speed of radio monitoring receivers*

Report ITU-R SM.2125 – *Parameters of and measurement procedure on HF/VHF/UHV monitoring receivers and stations*

3.5 Direction finders

3.5.1 General considerations

Identification of an unknown transmitting station can be facilitated if the location of the transmitter can be determined by triangulation or SSL using direction finder (DF) equipment. A more accurate determination of the transmitter location requires bearings to be taken by several DF stations established at suitable geographical locations. Ideally, a “cross bearing” or a “fix” (i.e. the point where the bearing lines intersect) can be obtained when a minimum of two DF stations, which need not necessarily be in the same country, work in unison. A monitoring station that has the possibility of taking bearings can provide an experienced operator with information, which will enable him to identify transmissions with a higher degree of confidence.

The complexity of the DF equipment depends upon the required accuracy and the local conditions and is discussed in more detail in § 5.7. Since the DF antenna should be set up at a place clear of any buildings, antennas, power and telephone lines and other prominences, it should generally be installed at some distance from the rest of the monitoring station, or perhaps at a separate location, where it is operated under remote control.

The accuracy of the bearings depends upon the following factors (not in order of importance):

– antenna aperture, as described in § 3.5.2;

– antenna configuration, including number of antenna elements, their organization into frequency bands, element directivity and other factors;

– type of DF equipment;

– number of receiver channels;

– nature of site;

– signal strength and *S*/*N*;

– integration time;

– propagation conditions;

– amount of interference.

In the frequency range where skywave propagation is present, typically 1-30 MHz, an SSL system allows determining the geographical position of a transmitter with a single radio DF that measures elevation as well as azimuth angle of arrival. Processing data supplied by the radio DF (azimuth, elevation, position), associated with ionospheric predictions or preferably real-time ionospheric measurements from a sounder, allows estimating the transmitter distance. The SSL concept thus allows performing the location mission when, for geographical, timing, availability reasons, a complete triangulation radio DF location system could not be installed, or the signal of interest could not be received at multiple stations.

For further information see Recommendations ITU-R SM.854 – Direction finding and location determination at monitoring stations, and § 5.7.

3.5.2 Antennas

The DF antenna is one of the most important components of DF equipment because it largely defines the DF accuracy. The aperture of the antenna array (D/λ; D: diameter of the antenna array, λ: wavelength of the received signal) plays a most important role in determining the bearing accuracy. DF antennas with $D/\lambda > 1$, so-called wide-aperture antennas, overcome multi-path problems and other propagation effects, noise, interference, site irregularities and other sources of error, providing higher *S*/*N*, smaller DF errors, higher immunity to reflections, higher sensitivity, and shorter integration times for a given level of accuracy than narrow-aperture antennas ($D/\lambda < 0.5$). Not all DF methods allow the use of wide-aperture antennas, but where they may be used, they provide the most accurate DF results.

Each DF antenna consists of a number of antenna elements (minimum three). Depending on the DF method various configurations of the DF antenna array are possible. Wider aperture DF antennas tend to have more antenna elements to fill the aperture and avoid ambiguities; the probability error introduced by random noise tends to reduce by the reciprocal of the square root of the number of elements. In the HF range circular and "L"- or "X"-shaped linear arrays are common, in the VHF/UHF range mainly circular arrays are in use. The DF method has also an influence on whether a wide frequency range can be covered by only one antenna array or whether the range has to be divided into a number of arrays for different sub-ranges.

Generally, one has to discriminate between DF antennas for fixed and mobile application. The type of antenna elements depends on the frequency range and application: in the HF range, arrays of monopoles or crossed-loop elements are used for fixed systems, whereas mobile systems use antenna arrays consisting of either loops or ferrite elements (see § 3.3.4.2). For the VHF/UHF range, mostly arrays of dipoles or fans are in use (see § 3.3.5.2).

3.5.3 Equipment

DF equipment may be integrated in with the measurement equipment at a monitoring station as described in § 3.7, or may consist of separate units. For portable units, see § 3.2. The frequency range of DF equipment is not only determined by the DF antenna but also by the receivers, which form part of the equipment. In practice, there is MF/HF DF equipment (e.g. 0.3-30 MHz) and VHF/UHF/SHF DF equipment (e.g. 20-6 000 MHz).

The number of receivers may vary from 1 to *n*, where *n* is the number of elements that form a DF antenna array and it depends also on the DF method. Multiple receiver systems require less integration time and/or less *S*/*N* for a given accuracy and therefore provide faster response time than single channel systems. If more than one receiver is used, all receivers have to be tuned by one common oscillator. In modern receivers, the IF is processed in digital form. A very important feature for DF receivers is the selectivity of the receiver to avoid a mutual interaction of two adjacent signals. At least one of the DF receivers should offer the possibility to demodulate the modulation of the received signal.

Some DF methods require a calibration of the receivers, RF distribution and antennas at certain time intervals. For this purpose, a defined signal will be injected in parallel into the receiving paths, and after measuring amplitude and phase for each path, corrective steps are taken to restore identical characteristics for each channel, if necessary. A very important feature is the possibility to remote control the equipment over any distance typically through a private network WAN or through the Internet.

3.5.4 Number of receivers

This section compares DF systems with varying numbers of receiver channels, considering the advantages and disadvantages of each. A DF system may have a single-channel receiver, dual-channel receiver, triple-channel receiver, or a receiver with up to as many channels as there are antenna elements. Systems with at least two receiver channels, but less channels than the number of antennas, are termed multi-channel systems. Systems with the number of receiver channels equal to the number of antennas are termed *N*-channel systems, where *N* is the number of receiver channels and antennas.

3.5.4.1 Single-channel systems

Advantages	Disadvantages
– Only one receiver channel required. – Less cabling from DF antenna to equipment. – No phase matching/calibration required. – For *interferometer* single-channel DF using multiplexing circuits, accurate phase measurement is possible.	– Amount of switching and associated sampling time require substantially more measurement time than DF systems with more than one channel. – Sensitive to rapid signal phase variations, which can result in bad data and/or long integration times. – If multiplexing circuits are used, antenna switch is complex.

Single-channel DF systems can be divided into two groups:

– simple single-channel DF systems, where each antenna element is sampled sequentially with one receiver channel; and

– interferometer or multiplexed single-channel systems, where the reference antenna element is sampled together with each other antenna element and both signals are combined and routed to one receiver channel.

In either case, after each switch, the IF filter in the receiver must be allowed to settle before the voltage can be sampled. The total sampling time depends on the settling time of the filter, which is tied to its bandwidth, and the number of antenna elements. This sampling time is substantially longer in single channel systems than in systems with more than one receiver channel.

During the sampling period in a single-channel system, the wave state of the signal could change due to changes in the internal modulation of the signal or effects of the propagation medium such as fading, multi-path and reflections that arise during the sequential sampling of the elements of the array. These wave-state changes during the sequential switching process can introduce errors in single-channel systems, because they may be indistinguishable from changes in the signal that arise from sequentially sampling antennas with different patterns or orientations of their main beam. The single-channel system can only deal with errors introduced by this mechanism through measurement of the signal over periods of time long enough to average out such effects. In cases where sufficient averaging time cannot be applied, such as in the case of short duration signals, single-channel systems can be confused. However, single-channel DF systems can be built that fulfil the requirement of 10 ms response time.

3.5.4.1.1 Simple single-channel DF systems

Simple single-channel DF systems sequentially sample each antenna element. In contrast to interferometer single-channel DF systems using multiplexing circuits, only amplitude is measured and processed. Phase is not measured. Systems that do not make use of phase information in the arriving wave are inherently less accurate than systems that use all the available information in the arriving wave.

3.5.4.1.2 Interferometer or multiplexed single-channel DF systems

Interferometer single-channel DF systems use a quadrature-multiplexing technique. This allows the measurement of amplitude and phase, since the phase-reference element is always measured together with all other antenna elements.

During the measurement process, in which all antenna elements are sampled one after the other, the amplitude of the signal could change due to changes in the internal modulation of the signal or effects of the propagation medium such as fading, multi-path and reflections. To avoid a decrease in accuracy, additional averaging is required. Furthermore, the amplitude difference between two antenna elements cannot be simultaneously measured and can only be obtained by averaging over time, losing information that would be useful in systems where directional antenna elements are employed.

After each switch between antenna elements and in the quadrature-multiplexer, the IF filter in the receiver must be allowed to settle before the voltage can be sampled. The total sampling time depends on the settling time of the filter, which is tied to its bandwidth, and the number of antenna elements. This sampling time is substantially longer in interferometer single-channel systems than in simple single-channel systems.

3.5.4.2 Multi-channel systems (one reference channel and one or more switched sampling channels)

Advantages	Disadvantages
– Requires less time to obtain a result than a one-channel DF, i.e. shorter response time. – Accurately handles changes in wave state due to propagation or modulation conditions. – Phase and/or amplitude matching are easily accomplished by calibration or double averaging method. – Simultaneously measures amplitude difference between channels.	– Two or more receiver channels needed; cabling is more complex. – Amount of switching and associated sampling time require more measurement time than DF systems with as many receiver channels as antennas. – Regular calibration needed to match both receiver channels or, for dual-channel systems, double averaging method may be used.

Multi-channel systems have more than one receiver channel, but less receiver channels than the number of antennas; they have one reference channel and one or more switched sampling channels. They have only one local oscillator, since all channels are driven from the same oscillator source. The channels do not have to be identically matched with filters which have exactly the same filter shape; rather, un-matched receivers may be used which are driven from the same oscillator. These receivers provide coherent detection of the signals in the two channels, and are calibrated over the entire RF path from antennas to A/D converters as to any phase delays, differences in the filter shape, etc., taking into account feed line differences between DF elements and the sampling circuits. This calibration is also the backbone of built-in test and diagnostics for such a system.

To avoid matching elements and/or calibration source and to simplify the measurement, but without the end-to-end calibration and built-in test, a double averaging method may be used in the case of two receiver channels, where a measurement of amplitude and phase difference between the two channels is made, and then the switching reverses the antenna connections and another amplitude and phase measurement is made, and the results are averaged, cancelling out any amplitude and phase mismatch without separate calibration. A disadvantage of this double averaging method is increased measurement time.

Since systems discussed here have a reference antenna and receiver channel that can serve as a reference for phase, the difference in phase between the sampled and reference channels can be precisely measured to an accuracy of one-tenth of a degree or better. The difference in amplitude between the sampled and reference channels can also be precisely and simultaneously measured, allowing the system to distinguish amplitude changes arising from any differences in directivity of the antennas, which single-channel systems cannot do without averaging over long periods to average out effects of modulation and propagation.

The measurement of voltage on each sampled antenna is compared with the voltage on the reference antenna measured at precisely the same time. Measurements on the sampled channel are normalized by the reference channel; the voltage on the sampled channel is divided by the voltage on the reference channel.

This normalization divides out the effects of propagation and modulation changes that introduce error as discussed above in connection with single-channel systems, since modulation and propagation factors affect each antenna equally, under plane wave reception conditions (usually assumed case). This normalization eliminates all external factors that may affect phase and amplitude measurement accuracy.

3.5.4.3 *N*-channel systems (*N* = number receiver channels = number antennas)

Advantages	Disadvantages
– Faster DF measurements than other methods. – No antenna switching is needed.	– Multiple receiver channels needed; cabling is more complex. – Need for phase and amplitude calibration increases complexity of the system.

N-channel systems with one receiver channel for each antenna are the fastest and highest performance systems, because the arriving wave can be sampled simultaneously on all antenna elements, rather than sampling the antennas sequentially as is done in systems with less receiver channels. All receiver channels are driven from one common local oscillator.

These systems are more costly than systems with less receiver channels, as a function of the number of receiver channels and the need to either phase match the channels, or to provide real-time calibration among them. The channels do not need to be precisely matched, but rather may be simply calibrated in real time.

N-channel systems measure voltages and phases on each element relative to one of the elements which is chosen as a reference, so they have all the advantages of systems discussed in the previous subsection in terms of being able to measure both phase and amplitude information relative to the reference element.

3.5.5 Bearing processing

Bearing processing can be based on different DF methods. Each principle has its advantages and disadvantages, depending on the application. The primary methods used are the following:

– Rotating antenna

– Doppler and pseudo-Doppler

– Adcock/Watson-Watt

– Phase interferometer

– Correlative interferometer

– Advanced resolution.

DF equipment produces a bearing with more or less accuracy and will also indicate the receiving level of the signal to which the system is tuned. Some DF equipment produces for each bearing a quality value that can be used to suppress “wild” bearings. Phase-sensitive DF equipment for the HF range indicates also the elevation angle of the received signal if it arrives as a sky wave.

One very important feature of modern DF equipment is the ability to operate in a “DF scan” mode. With this feature, it is possible to scan through defined frequency ranges performing spectrum occupancy and simultaneously calculating the associated bearings of any signals above a threshold. This DF scan function is performed with DSP where Fast Fourier Transform (FFT) techniques are applied to subdivide the receiver bandwidth into many individual channels or FFT bins. Occupancy information and voltage information for a DF processing technique are computed by the FFT for each individual channel.

This processing technique makes it possible to intercept short-duration transmissions such as frequency hopping and burst emissions. DF scan is discussed and illustrated near the end of § 3.7.2.

3.5.6 Typical specifications for DF systems

A direction-finding system should generally meet the specifications for MF/HF and VHF/UHF DF systems that are given in Tables 3-5 and 3-6. One should consider these specifications as a general guideline to select equipment that is able to provide good performance and reliability for the tasks required by a DF system.

Chapter 3 of Report ITU-R SM.2125 provides information on testing of specifications for DF station IP_2, IP_3, sensitivity, angular accuracy, scanning speed and minimum signal duration.

Some of the specifications may vary, or may not even be applicable, depending on the types of emissions to be encountered and/or the application for the direction finder. For example, a direction finder to support fast scanning of the radio spectrum should have the DF interception scanning speed as given in the table. However, a direction finder that is used only for DF homing in a mobile environment would not need to have a fast scanning speed.

As another example, a short minimum signal duration (response time) may be required where short duration signals are encountered or in cases of rapid scanning of the spectrum, but a longer minimum signal duration may be acceptable in cases such as homing on a particular emitter. It should also be noted that shorter signal collection times help with propagation-related effects such as multipath that can change rapidly and help mitigate interference, and it is more accurate to take lots of "snapshots" of a signal, each over a short enough period that the propagation and interference effects will not have changed, and average the results, than it is to take a few snapshots of the signal, each over a longer data-collection period.

TABLE 3-5

Specifications for typical MF/HF DF fixed and mobile stations

Function/Performance (non-exhaustive list of parameters)	**Fixed station** (300 kHz – 30 MHz)	**Mobile station** (1 MHz – 30 MHz)
DF bearing accuracy of the system (tested on open-air test facility in reflection-free environment, as per Recommendation ITU-R SM.2060)	1° RMS (f > 1 MHz), groundwave; 2°/cos(elevation) RMS, skywave	5° RMS (1 MHz – 10 MHz); 2° RMS (10 MHz – 30 MHz), groundwave, system installed in vehicle, test in reflection-free environment
Single Site Location (SSL)	Optional (needs ionospheric data, see section 5.7)	(not applicable)
DF interception scanning speed (refer to definition in paragraph 3.3.2 of Report ITU-R SM.2125; applicable to scanning DF systems)	50 MHz/s, 5 kHz channel BW and 50% channel occupancy	50 MHz/s, 5 kHz channel BW and 50% channel occupancy
DF modulations	All	All
DF instantaneous bandwidth	≥ 500 kHz	≥ 500 kHz
DF Sensitivity	2 µV/m (f> 1 MHz) referred to 250 Hz DF bandwidth, 1 s integration time and 2° RMS accuracy	30 µV/m (f > 1 MHz) referred to 250 Hz DF bandwidth, 1 s integration time and 2° RMS accuracy
Minimum signal duration (refer to definition in paragraph 3.3.3 of Report ITU-R SM.2125)	5 ms to 10 ms	5 ms to 10 ms

NOTES:

Specifications for frequency tuning error, receiver noise figure, 3rd order intercept (IP_3), IF bandwidth, and operating temperatures are described in Tables 3-3 and 3-4.

The bearing accuracy specification for skywave signals is dependent on the cosine of the elevation angle of arrival because as the elevation angle becomes higher, the great circle arc covered by an azimuth degree becomes smaller in accordance with cos (elevation), and in fact at 90° elevation, the great circle arc covered by an azimuth degree goes to zero.

TABLE 3-6

Specifications for typical VHF/UHF DF fixed, mobile and transportable stations

Function/Performance (non-exhaustive list of parameters)	**Fixed station** (20 MHz – 6 000 MHz)	**Mobile station** (20 MHz – 6 000 MHz)	**Transportable station** (20 MHz – 6 000 MHz)
DF bearing accuracy of the system, (tested on open-air test facility, as per Rec. ITU-R SM.2060)	1° RMS in scatter- and reflection-free environment, including lightning protection	3° RMS in scatter- and reflection-free environment, system installed in vehicle, DF antenna on roof, not extended 1° RMS in scatter- and reflection-free environment, DF antenna on mast extended	2° RMS in scatter- and reflection-free environment, system mounted on a tripod
DF interception scanning speed (refer to definition in § 3.3.2. of Report ITU-R SM.2125; applicable to scanning DF systems)	1 GHz/s, 25 kHz channels, 50% channel occupancy	1 GHz/s, 25 kHz channels, 50% channel occupancy	1 GHz/s, 25 kHz channels, 50% channel occupancy
DF modulations	All	All	All
DF instantaneous bandwidth	≥ 20 MHz	≥ 20 MHz	≥ 20 MHz
DF sensitivity 20 MHz to 3 000 MHz 3 000 MHz to 6 000 MHz	 10 µV/m 25 µV/m referred to 1 kHz DF bandwidth, 1s integration time and 3° accuracy parameters as per Rec. ITU-R SM.2096, average over band	 10 µV/m 30 µV/m referred to 1 kHz DF bandwidth, 1s integration time and 3° accuracy parameters as per Rec. ITU-R SM.2096, average over band	 35 µV/m (20-300 MHz) 20 µV/m (300-3 000 MHz) 30 µV/m referred to 1 kHz DF bandwidth, 1s integration time and 3° accuracy parameters as per Rec. ITU-R SM.2096, average over band
Minimum signal duration (refer to definition in § 3.3.3 of Report ITU-R SM.2125)	1 ms	1 ms	1 ms

NOTE 1 – Specifications for frequency tuning error, receiver noise figure, 3rd order intercept (IP_3), IF bandwidth, and operating temperatures are described in Tables 3-3 and 3-4.

NOTE 2 – DF accuracy measurement procedures use signals of signal to noise ratio > 10 dB as discussed in § 5.7.

3.6 Additional measuring equipment and standards

Most spectrum monitoring stations use automated, integrated systems described in § 3.7. These systems make the ITU-recommended measurements of frequency, field strength, bandwidth, and modulation, as well as spectrum occupancy and DF/TDOA measurements, with integrated measurement equipment. However, instead of or complementary to these automated, integrated systems, additional and separate equipment is also available to perform these measurements and to assist in identification. Some of this equipment is discussed below.

3.6.1 Time and frequency standards

Frequency is the most important emission characteristic that needs to be measured by a radio monitoring service. The required accuracy is quite dependent on the purpose of the measurement. When the purpose is to quickly check the use of the proper channel of narrowband FM voice radios at major events, it may be sufficient to use simple handheld frequency meters with accuracy of about 10 Hz. In contrast, when compliance with ITU-R Recommendations or national provisions is to be verified, the required accuracy may be very high.

Frequency-measuring instruments are generally provided with a free-running crystal standard. The output frequency of the crystal stage depends upon the ambient temperature and the operating voltage. Even after the warm-up period, a crystal oscillator shows a steady variation of the output frequency which can be on the order of 10^{-8}. For high-quality instruments, the steady variation of the crystal frequency is between 10^{-10} and 10^{-9} per day after a continuous warming-up time of several weeks. Consequently, instrument crystal stages must be periodically compared with primary frequency standards, or must be directly controlled by a standard frequency emission provided by a standard frequency and time signal service (SFTS), that operates in accordance with No. **1.53** of the RR or a standard frequency and time signal-satellite service (SFTSS), that operates in accordance with No. **1.54** of the RR.

This last alternative is the most adopted by spectrum monitoring solutions, which incorporates a RNSS disciplined oscillator as a time and frequency reference.

3.6.1.1 Global Navigation Satellite System disciplined time and frequency references

Each Global Navigation Satellite System (GNSS) satellite carries two caesium clocks on board that are synchronized by their master station. If used for time and frequency comparison, the time error is much lower than 1 μs, usually the average error value is about 10 ns. A time error of 1 μs per day corresponds to a frequency error of 10^{-11}. For spectrum monitoring, it is recommended to control a local crystal oscillator or atomic standard by an appropriate GNSS receiver. A typical frequency accuracy of 5×10^{-12} (10 MHz output) can be achieved by using a GNSS-disciplined Rubidium standard, while not affecting the short-term stability of the local oscillator.

More detail on GNSS systems can be found in § 7.1 of Chapter 7.

3.6.2 Spectrum analysers

A spectrum analyser measures the distribution of signal power over frequency. Unlike oscilloscopes, which display amplitude versus time, spectrum analysers display amplitude (vertical axis) versus frequency (horizontal axis). This allows users to observe characteristics such as dominant frequencies, power levels, distortion, harmonics, and bandwidth- features that are difficult to detect in the time domain.

Spectrum analyser types are distinguished by the methods used to obtain and analyse the spectrum of a signal. The different types are described in the following sections.

Although all types of spectrum analysers are available as benchtop devices, detecting and locating interference in the field often requires using a handheld, battery powered spectrum analyser with a directional handheld antenna.

3.6.2.1 Swept spectrum analysers

A swept-tuned analyser uses a superheterodyne receiver to convert a portion of the input spectrum into the so-called resolution bandwidth (RBW) of a narrow filter. By sweeping the receiver's frequency across a range (span), the analyser builds a complete spectrum display. The time required to complete a full sweep (sweep time) needs to be slow enough for the RBW filter to settle on each frequency step. The biggest advantage of traditional analogue sweep is the excellent selectivity and dynamic range. Large spans can be swept to detect low level spurious signals, and the sweep time can be precisely controlled. However, because the analyser focuses on one frequency at a time, short-duration events at other frequencies may be missed.

3.6.2.2 FFT analysers

An FFT (Fast Fourier Transform) analyser captures and samples time domain data for a certain time (acquisition time) and computes the spectrum using FFT algorithms. Typically, the RF signal is first fed to a mixer to lower the effective centre frequency for manageable sampling. Unlike swept spectrum analysers, FFT analysers can capture all samples within the available bandwidth continuously, making them well-suited for detecting transient or pulsed signals. Because all frequencies are captured at the same time, high resolution spectra are available much faster than with swept spectrum analysers. However, achieving high amplitude accuracy and dynamic range is challenging. For spans that are larger than the capture bandwidth, FFT analysers typically apply multiple captures in frequency steps equal to the capture bandwidth and display a "stitched" total spectrum. For details on the FFT principle, see § 7.7.

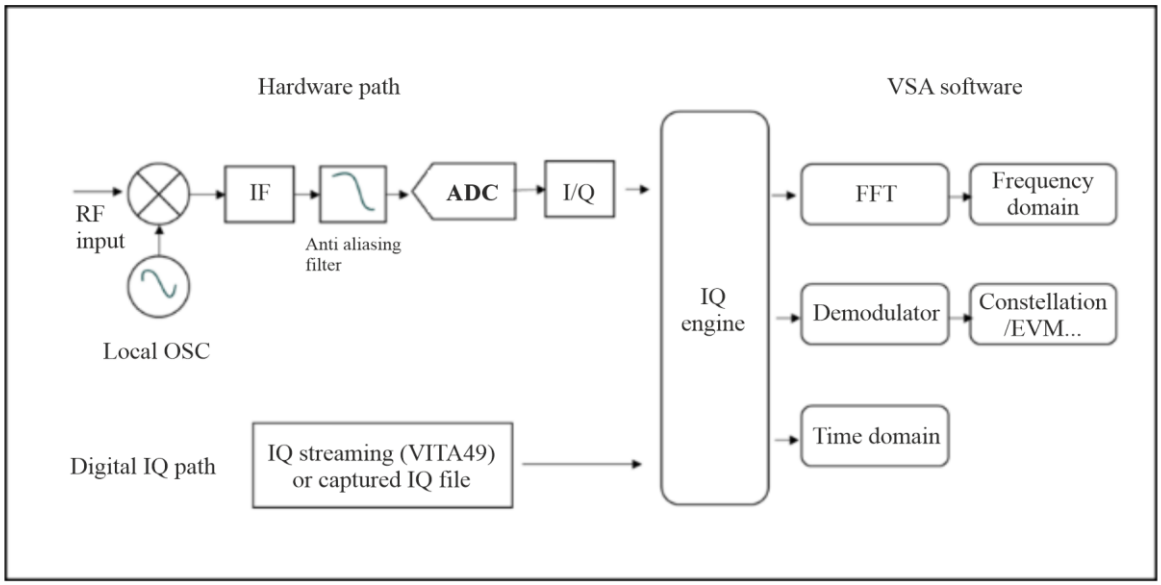
3.6.2.3 Vector signal analysers

Apart from the amplitude, the FFT process also delivers the phase of an RF signal. This combination provides possibilities for spectrum, time-domain, and modulation analysis on complex, digitally modulated signals, called Vector Signal Analysis (VSA).

Vector signal analysis can be integrated into FFT analysers, or function as a standalone software application. When integrated into an FFT analyser, VSA can be performed either on live RF data from the hardware path, or on previously recorded I/Q data. Figure 3-35 shows the key elements of a VSA analyser.

FIGURE 3-35

Block diagram of a typical vector signal analyser



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VSA software can process data to provide measurements in the:

frequency domain

– spectrum, spectrograms, channel power, occupied bandwidth;

time domain

– pulse rise/fall time, Pulse width, duty cycle;

– time-gated measurements;

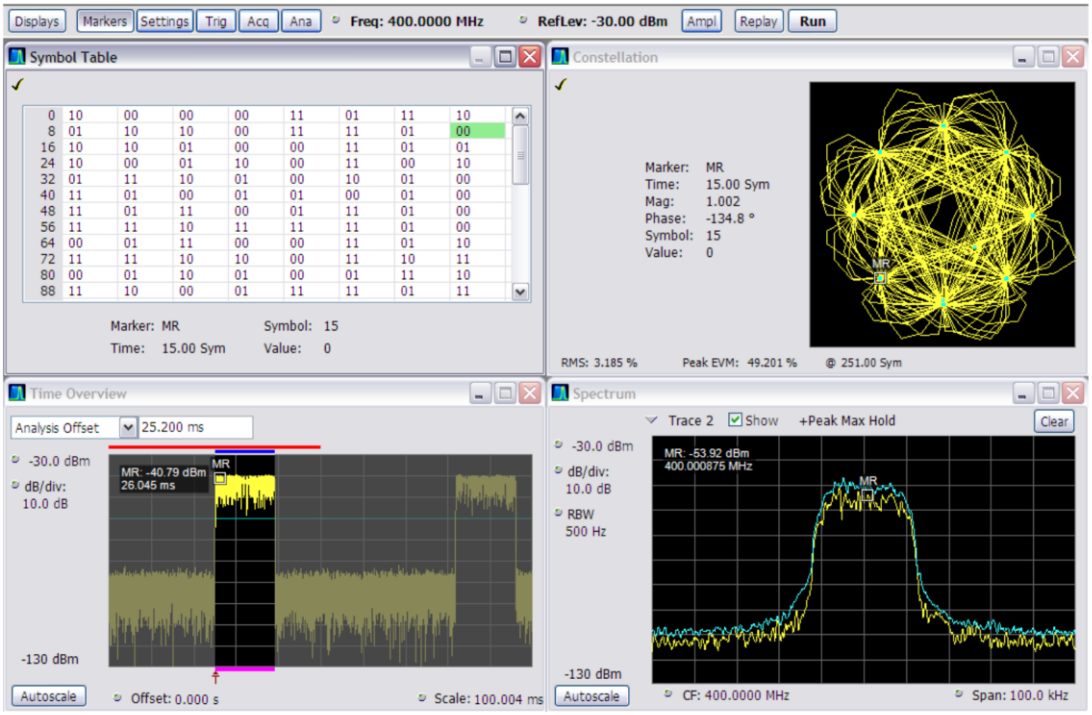
modulation domain

– modulation analysis, constellation measurement.

Figure 3-36 shows an example of a VSA on a TETRA base station signal. The bottom left shows the time domain where a whole burst of 14 ms is captured and analysed (time indicated by the blue bar on top). The top right window shows the vector and constellation diagram during the analysed time interval. The top left window shows the binary code of signal, and the bottom right window shows the spectrum during the whole analysis time (turquoise). The yellow trace shows the spectrum only during a selected time of the training sequence (in the range that is not greyed in the time domain window).

FIGURE 3-36

Vector signal analysis example of a TETRA signal



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If a protocol sniffer supporting I/Q data input is employed, VSA can also decode system information such as Radio Resource Control (RRC) messages and provides many different quantitative and qualitative analyses of the signal and its modulation schemes (see Fig. 3-37).

FIGURE 3-37

Vector signal analysis example of a 5G NR signal

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Modern wireless signals like LTE and 5G New Radio have multiple modulation schemes running simultaneously and transmitted via MIMO through an Advanced Antenna System (AAS). VSA can display constellations (top left, Fig. 3-37) and EVM (bottom middle) which indicate the quality of the modulation. It can also show the physical cell ID(PCIs), provide information on each individual physical channel, its quality, and channel allocations in time vs. frequency domain (top right, Fig. 3-37). This helps spectrum management professionals examine both the physical spectrum transmission as well as the associated digital signal qualities.

3.6.2.4 Real-Time Spectrum Analyser (RTSA)

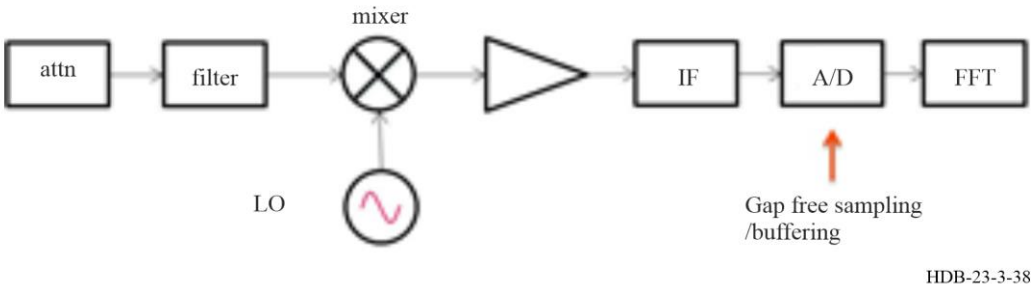
Typically, FFT analysers work in “block mode”: First, the signal is captured for an adjustable time, then the FFT calculation process is applied on the captured data. Depending on capture bandwidth and required frequency resolution, the FFT computation may take longer than the actual capture time. In that case, continuous (gap free) acquisition of an RF signal is not possible because during the computation time, signals at the RF input will be lost. On the other hand, setting the acquisition time longer than theoretically required for an FFT, different amplitude detectors such as peak, average and RMS can be realized by using multiple FFTs available in an acquisition block.

A Real-Time Spectrum Analyser (RTSA) uses a circular buffer to continuously store gap-free I/Q data blocks. At the same time, it runs a high-speed FFT to ensure all I/Q data in the buffer is represented in the spectral display. An RTSA is not designed for complex measurements like demodulation or channel power. Its goal is to detect RF energy.

Figure 3-38 shows a simplified block diagram of an RTSA.

FIGURE 3-38

Simplified block diagram of a real time spectrum analyser

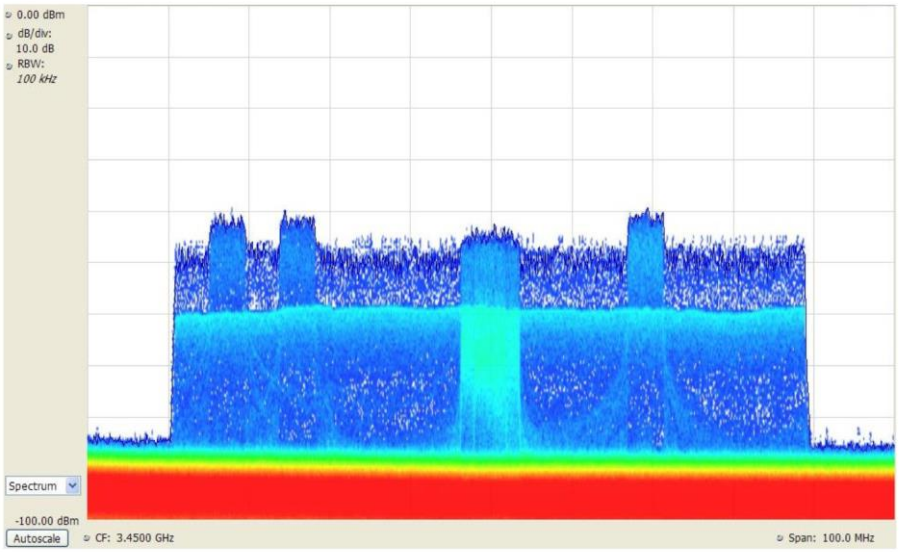


RTSA's centre frequency is not designed to be tuneable during the measurement in order to maintain a gap free spectrum, so the span is limited by the IF bandwidth and ADC sample rate. Additionally, RTSA's RBW does not follow the traditional 1-3-10 kHz sequence but rather is tied to the ADC sample rate and SPAN setting, so users should be aware of this during measurements.

One of the most valuable features of an RTSA is the possibility to show so-called "density", "polychrome" or "persistence" spectrum. Amplitude vs. frequency is shown in a way that the probability of certain amplitudes is indicated by different colours, typically in a temperature scale: Amplitudes that occur often (e.g. CW signals) appear in red, while amplitudes occurring seldom or for a short time (e.g. pulses) appear in blue. Figure 3-39 shows an example of such a display.

FIGURE 3-39

RTSA persistence spectrum display of a 5G NR signal



For spectrum monitoring, RTSAs can:

– detect and display hard to capture time-variant signals, like pulses, uplinks, and intermittent emissions;

– visualize and identify co-channel interference with density and persistence displays;

– examine the time domain characteristics of modern wireless transmissions like 5G/LTE control channel allocation to determine the presence of an interfering emission;

– detect and display the frequencies of uplink signals from rouge mobile devices. These emitters can be located using a directional antenna and "walking it down".

There are two key performance parameters unique to RTSA. The first is the minimum duration signal with 100% probability of intercept (POI). This parameter scores the capability of a RTSA to measure a short, pulsed signal and correctly measure the power level (typically microseconds). The second is the minimum detectable signal duration which scores the RTSA's capability to simply detect the shortest pulse width without specified power accuracy (typically nanoseconds).

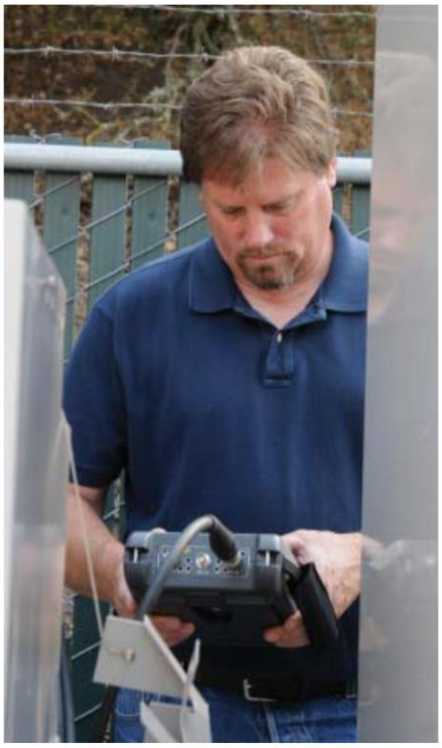
3.6.3 Handheld (HH) Vector network analyser (VNA) and cable antenna tester

All monitoring stations rely on the performance and proper maintenance of key RF components such as antennas, cables, filters, RF switches and connectors. They have profound impact on the monitoring stations' ability to detect and accurately measure RF emissions and locate interference.

Verifying the performance of these key components requires a vector network analyser capable of measuring S parameters (giving return loss, insertion loss and phase information) and sweeping cables and antennas for faults. It is not always feasible to carry lab-grade bench top equipment to the field. Also, such equipment is typically designed to operate only at room temperature.

FIGURE 3-40

Cable sweep in the field with handheld VNA



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Rugged handheld vector network analysers (Figure 3-40) and cable antenna testers are designed to be lightweight, portable, operate in wide temperature ranges, and are fully sealed against intrusion of water and dust. They are specifically designed to test RF components in the field and can easily be carried to a monitoring station and access measurement points outside.

FIGURE 3-41

VNA measurements of insertion loss, smith chart and phase of all 4 s-parameters

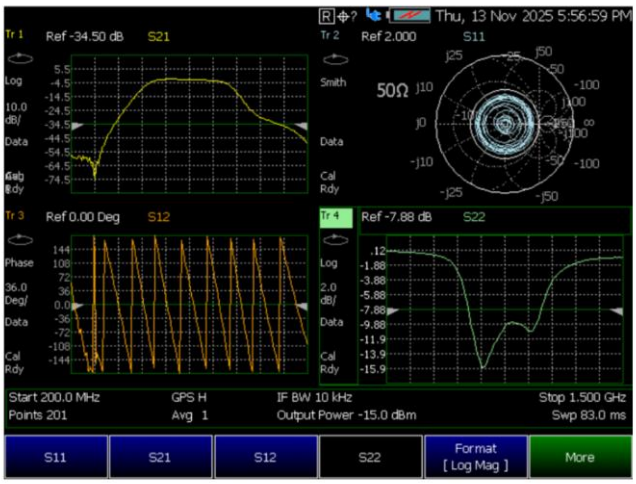

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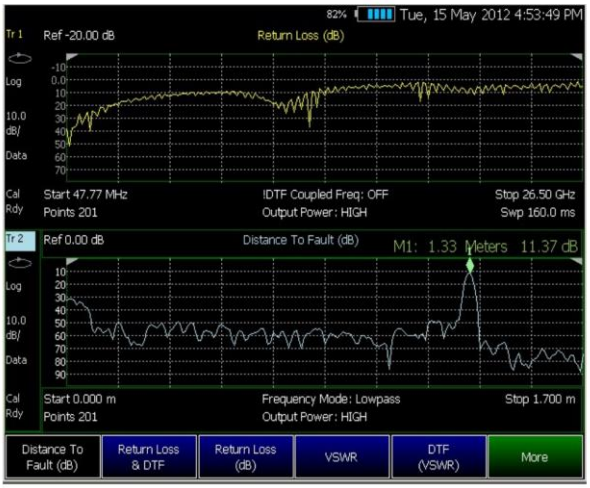
FIGURE 3-42

Return loss (upper) and distance to fault (lower) measurements



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HH VNA/cable antenna tester can perform the following measurements in the field (Figs 3-41 and 3-42):

– Antenna VSWR/Return Loss to make sure antenna performs at its best efficiency.

– Cable loss – RF feedline loss directly impacts the monitoring station overall noise figure, so this is very important to check.

– Distance to fault (DTF) and time domain reflectometer (TDR) measurements can be used to troubleshoot faulty cables or antennas, and to locate major reflections in the system due to an open, short, or water leakage in cable insulation.

– Frequency and phase response measurements can be used to verify filter performance. It is very common in public safety networks to re-tune filters due to licensed frequency change. Also, band pass and notch filters are useful tools to mitigate the effects of interference or strong nearby emitters.

– For monitoring stations with more than one antenna connected, antenna isolation measurements are important. A 2-port VNA can measure antenna isolation is important to ensure monitoring antenna installations are optimized in terms of frequency coverage. It can also help spectrum engineers make an educated compromise to reduce the number of antenna if space is limited.

3.7 Digital signal processing equipment and associated software

3.7.1 Introduction

Before the advent of Digital Signal Processing (DSP) technology, the various ITU-recommended measurements were performed by separate pieces of test and measurement equipment:

– *Frequency* was often measured with a frequency counter, although several other frequency measurement methods exist as are described in § 5.2.

– *Field strength and RF level* were often measured with a power meter.

– *Occupied Bandwidth* could be measured by observing the x-dB bandwidth on a spectrum analyser.

– *Modulation metrics* could be measured with a modulation analyser to obtain the appropriate parameters for a given modulation type.

– *Direction finding* was performed with stand-alone direction-finding equipment.

– *Spectrum occupancy* was typically measured with a spectrum analyser/monitoring receiver station.

Each of these separate pieces of equipment had its own front panel, to request measurements and display the results of each measurement. Therefore, to make all the ITU-recommended measurements required quite a collection of separate test and measurement equipment, with each piece of equipment separately controlled and separately reporting its measurement results.

As personal computers became available, the above-listed equipment also became available with computer interfaces, so the individual test and measurement equipment could be controlled by a single central processing unit that would gather measurements results, store, analyse then and produce reports, although each separate piece of equipment still had its own front panel, from which measurements could be requested and results could be observed and studied.

As computers became more powerful, it became possible to perform more of these measurements digitally, rather than with analogue test and measurement equipment. A signal of interest could be digitized, obtaining a detailed representation of it that includes both amplitude and phase information (also known as in-phase and quadrature or I&Q information). The digitized information could be processed to produce the desired measurement quantities using algorithms that perform transformations equivalent to those obtained by the analogue measurement equipment.

This is the essence of DSP; details of the techniques to extract each of the desired measurement parameters (frequency, field strength, occupied bandwidth, etc.) are described in Chapter 5 of this Handbook. The result of this DSP revolution has been to replace the various test and measurement equipment that makes the individual measurements listed above with a compact processor that includes a variety of separate modules including receiver channels, A/D conversion, digital signal processing and demodulation, GPS receiver, workstation interface, and other modules, all inside of one chassis.

This Digital Signal Processor typically does not have any front panel to replace the front panels on all of the individual pieces of test and measurement equipment; rather, the individual-equipment front panels are replaced by virtual front panels as described and illustrated below. These virtual control panels appear on the display of the control device for the DSP. After discussing the processing equipment, the balance of this section describes the virtual control panels and basic measurement functions using them.

In addition to the primary Digital Signal Processor (DSP), additional dedicated Digital Downconverters (DDCs) are integrated to handle narrowband signals using extracted I/Q data. These DDCs process the I/Q data, facilitating automatic signal analysis to identify characteristics such as modulation types or ITU radio service classifications. The inclusion of this extra processing, particularly the I/Q data, requires the processor to be configured with access to significantly larger on-board storage capacities, ranging from gigabytes to terabytes.

Chapter 4 describes the powerful capabilities that are made possible by the DSP revolution, discussing computerized monitoring networks and networked spectrum monitoring, data collection, processing and analysis, artificial intelligence and big data as applied to spectrum monitoring, integrated computerized national systems including remote access to system resources, and integration with spectrum management including automatic violation detection.

3.7.2 Station functions

DSP-based stations generally perform the functions of a fixed monitoring station, as described in § 3.2. All routine monitoring measurements are repetitive tasks that lend themselves easily to DSP data collection and processing:

– *Occupancy measurements*: Fine-resolution scanning of the frequency bands with computer-generated displays and storage capacity of channel occupancy over several days is well suited to DSP collection and processing. The use of wideband digitizers in combination with consecutive FFT of sampled I/Q data enables faster scanning allowing higher POI where required.

– *Frequency, bandwidth, level, and field strength measurements*: These can be made with DSP when the *S/N and resolution* is sufficient. Precise frequency measurement often relies on transmissions with carrier frequency. At HF, channels are usually very closely spaced; thus sharp frequency selectivity should be provided in the case where several frequencies are present in the same channel.

– *Signal analysis*: Advancements in DSP hardware and algorithms have led to the development of modulation recognition or classification systems which identify modulation types in real-time as shown in Fig. 3-43. These systems may be implemented in stand-alone instruments, computer add-in cards and associated software, or may be integrated into other instruments (such as receivers or analysers). These systems can be used to recognize various modulation formats (both digital and analogue), measure common technical parameters, and demodulate or decode the signals.

– *Manual modulation parameter measurements*: The capability for fully manual measurements of modulation parameters with high resolution is nevertheless recommended by Recommendation ITU-R SM.1600-1 and can be provided by suitable software based on recorded I/Q data as illustrated in Fig. 3-44.

– *Direction Finding* (*DF)/Angle of Arrival (AOA)/Time Difference of Arrival (TDOA), geolocation*.

– *Station identification*: through location, message content information, or automatic signal analysis (code recognition, number of elements, transmission rate). In a fully automated system this usually necessary preceding recognition of modulation and prioritisation of emissions. In order to identify a station based on its transmitted meta data like callsign or station ID, demodulation and partial decoding is needed; such systems can be based on hardware decoders, specific DSP/FPGA implementations or, most conveniently, SDR concepts.

FIGURE 3-43

Example of detection and classification of multiple signals

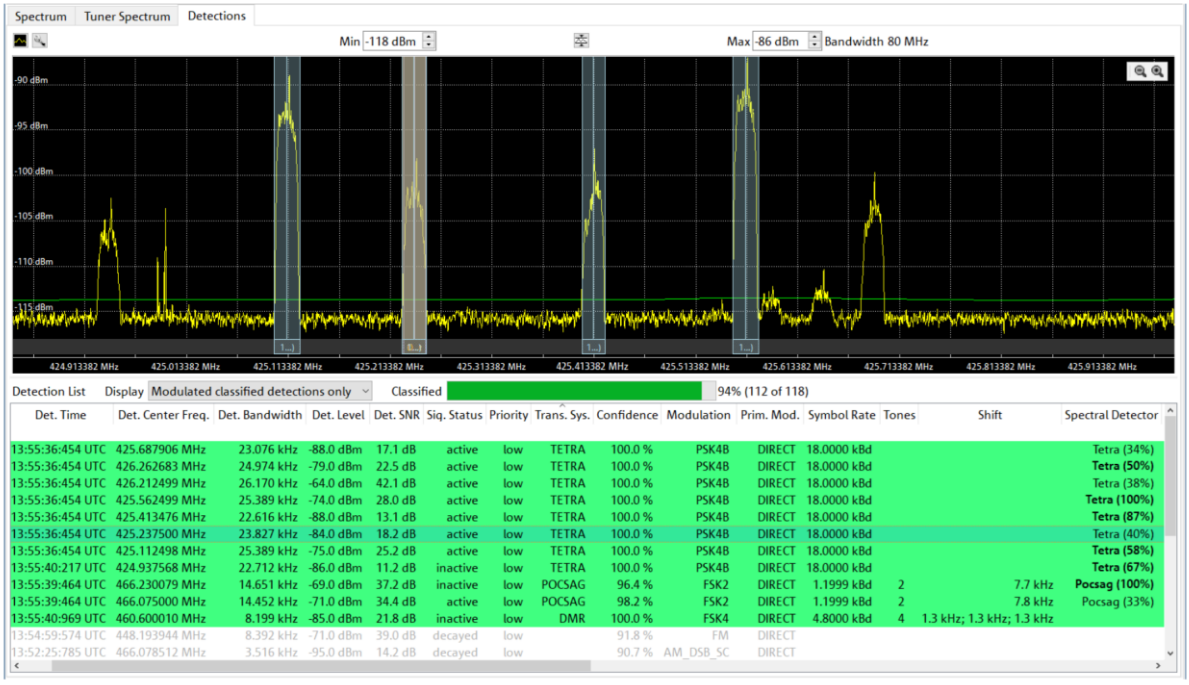

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FIGURE 3-44

Manual measurement of modulation parameters consistent with ITU-R SM.1600-1

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3.7.3 Monitoring station equipment and operation

DSP techniques allow economical and efficient monitoring stations which consists simply of:

– a small group of sophisticated measuring equipment, including digital receivers and processors; and

– operator workstations, often referred to as clients, which are used for operator interface, and which contain computer software that make the system easy to use and easy to maintain.

Spectrum monitoring stations can be operated either locally or be remotely controlled from a more convenient location, using radio or terrestrial data links. Essentially, the monitoring stations become nodes on a wide area network (WAN) operated and administered by the control stations.

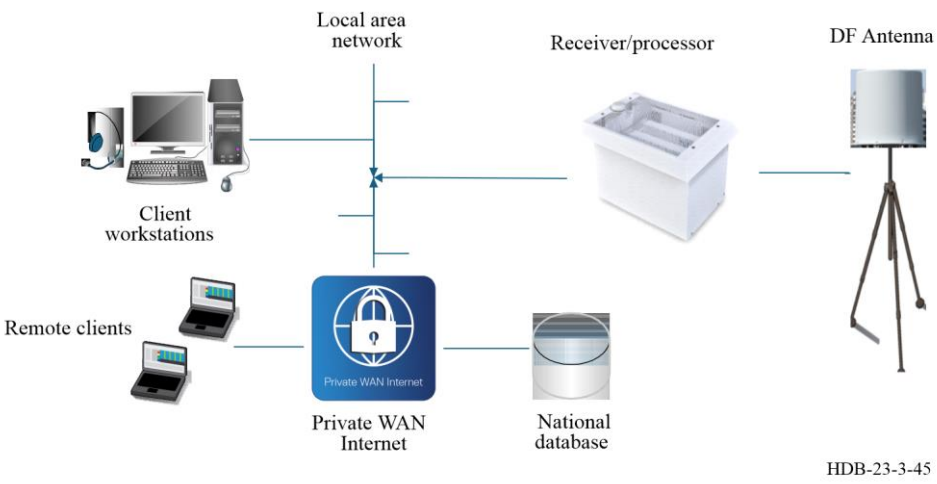
A modern DSP-based station typically has the architecture illustrated in Fig. 3-45. This illustrates a station with its antennas connected to a receiver/processor unit that is connected to a local area network (LAN) within the station. This network may include the client workstation in addition to being connected the organizational private Wide Area Network enabling other clients to remotely control the station and also allowing the station equipment to share data with any national databases.

Due to the remote operation capabilities, modern monitoring stations are often unattended, with no human interface on site, and solely operated by remote clients. On such stations, instead of the client workstation, one may find a general-purpose computer to perform autonomous tasks and locally store data, extending the capabilities of the receiver/processor unit and providing more reliable and stable operating conditions for autonomous task, that are not dependent on the remote access links.

These autonomous tasks may include dedicated activities triggered by scheduled measurements when a deviation from the expected signal scenario is automatically detected, e.g. run location task as soon as interferer is active. Also, classification based on I/Q data can run autonomously on the remote sites to minimize network load and requirements.

FIGURE 3-45

Typical modern integrated radio spectrum monitoring station



The DSP based processor and receiver unit has the necessary capabilities for receiving the signal, digitizing the spectrum, processing the measurement results and doing the DF processing.

Monitoring stations as depicted can perform all standard functionalities, such as:

– monitoring, demodulation and decoding;

– I/Q spectrum and audio recording;

– technical measurement and analysis including frequency and frequency offset, level/field strength, modulation parameters including AM modulation depth and FM frequency deviation, bandwidth, and spectrum analysis;

– spectrum occupancy;

– DF and emitter location;

– automatic real time comparison with licence parameters;

– automatic alert generation on abnormal or unknown transmissions.

3.7.4 Typical modes of equipment operation

Spectrum monitoring stations typically have three modes of operation which are used to perform these tasks:

– *Mode 1*: Interactive or real time operation.

– *Mode 2*: Automatic scheduled operation.

– *Mode 3*: Automatic background operation.

3.7.4.1 Interactive or real time operation

Interactive operation is an essential part of the spectrum monitoring services as described in Recommendation ITU-R SM.1050. Such mode of operation is required to perform many of the regular spectrum monitoring activities, being essential for those of more investigative nature, such as the identification of sources of harmful interference and unauthorized transmitters.

Manual and interactive mode allows direct interaction with various receiver parameters and provides instantaneous feedback such as monitoring receiver tuning, demodulation selection, and panoramic-display selection, allowing users to dynamically adapt the receiver and activity parameters in accordance with the changing propagation environment, emitter configuration and any other unpredictable conditions.

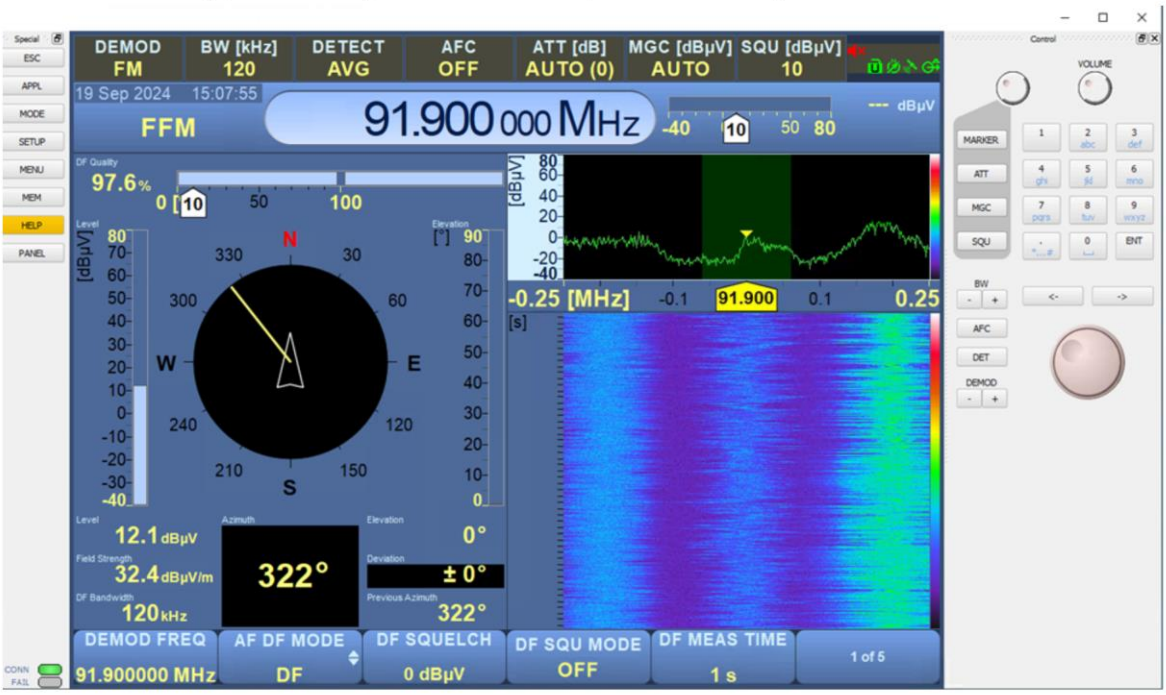
Interactive functions are usually controlled through a Graphical User Interfaces (GUI) sometimes just referred as User Interface (UI), such as is illustrated in Fig. 3-46. At this simple example, buttons, knobs, text fields and graphical interaction with the mouse allow the user to control the DF receiver, which presents results in the form of graphics, audio, and text.

Using such interactive virtual control panels on the client workstation, the operator can inspect synthetic panoramic and spectrum displays and include waterfall displays (three-dimensional displays of signal amplitude, versus frequency, versus time) and spectrogram displays (two-dimensional displays of signal frequency versus time, with signal amplitude indicated by colour).

FIGURE 3-46

(a) Example of a virtual control panel for monitoring receivers

(b) Example of a virtual control panel for monitoring receivers with DF



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DF homing is an important example of interactive operation. DF may be commanded in a mobile unit as the unit is in motion. DF results are presented with respect to the front of the vehicle, as illustrated and described further in § 5.7.3.3, and allow the driver to decide which direction to drive to approach the desired signal transmitter. DF results from different locations are also displayed on a geographic map, allowing triangulation by the system to locate the signal transmitter. A high precision GPS receiver continuously updates the exact location of the mobile unit, and an electronic compass measures the orientation of the vehicle with respect to North.

Within a spectrum monitoring network is also possible to collect real-time measurements from multiple monitoring stations by a central control station, allowing for greater flexibility and more advanced processing, including emitter location using methods such as TDOA and AOA, including the hybrid, or combined AOA and TDOA, emitter location described and illustrated in § 5.7.3.6.

3.7.4.2 Automatic operation, scheduled and background

Several of the spectrum monitoring activities described in Recommendation ITU-R SM.1050 may be accomplished by a fully automated, non-attended system, with great operational benefit when such tasks require continuous monitoring through long periods and off hours.

Maintaining continuous monitoring of radio transmission activity may be a requirement for specific bands in certain locations. This includes rapid identification and location of transmitters for elimination of interferers and unauthorized users in sensitive areas, such as the protection of aeronautical and maritime services, and for various emergency and security channels used by public safety agencies, military and civil protection services.

This type of spectrum protection requires a radio monitoring system capable of operation with fast scanning of the spectrum, being desirable the ability to perform geolocation or DF of active signals, with online alert system to enable rapid response from authorities and field teams.

In addition to just alerting, these systems should be able to automatically perform dedicated measurements once an incident has been detected. These measurements may include recording of the signal to identify the interferer or extended monitoring of technical parameters to prove how long a transmitter has violated its license constraints.

It is also not uncommon to see that unauthorized user of spectrum, especially in the broadcast bands, concentrate their operations during weekends and after working hours, due to the increase in the potential listeners and as an attempt to evade official attention. The characterization of such activity through automated means can also be a benefit in the use of unattended monitoring stations.

Finally, spectrum monitoring may also be tasked to gather information for spectrum management about the usage of various bands of interest, including the characterization of behaviour patterns, such as night and day changes, workdays and weekends, or even seasonal changes, which will require the use of automated stations for data collection during extended periods.

3.7.4.2.1 Scheduling and prioritizing

The coordination of multiple measurement requests to the monitoring stations usually follows best effort principles with different priorities assigned to the tasks by the users, either directly or through pre-defined configuration.

Such configuration allows the automation within the monitoring system to allocate the limited measurement equipment resources in accordance with predefined rules, allowing the various modes of operation, real-time, scheduled and background.

Interactive operation usually will take higher priority to avoid excessive delay to user requests and with the understanding that users will be aware of the impact of their requests on pre-defined tasks. To make sure that such impact is known, usually the user interface provides some feedback as to the number of tasks currently under execution, planned, and the available resources and similar information.

Activities performed under automatic mode may include any measurement that the system might be able to carry on without human intervention. The activities may be initiated immediately, as a sequence of manual operations, or in scheduled fashion, with pre-defined start and stop dates and times.

User interface may include controls such as record/start, pause and stop to control the automatic tasks, or a calendar with dates, time and recurrency to control the task execution in scheduled fashion.

Scheduling may be performed for a single monitoring station or to a group of networked stations. The ability to coordinate the priority of a schedule to ensure that critical tasks are executed is a useful feature to coordinate tasks.

Low priority, permanent schedules may be created, which is known as a background mode of operation. Such tasks can be useful to maintain an elevated level of awareness about the spectrum availability, with the aid of Automatic Violation Detection (AVD) algorithms.

Low-priority tasks may also be used to provide regular maintenance checks through the monitoring of known transmitters and execution of hardware self-test protocols.

Scheduling and task programming may also take the form of measurement scripts, which may be saved as files, allowing measurement tasks to be shared and reused in multiple stations, helping to standardize procedures within an organization.

3.7.5 Examples of equipment operation

Sophisticated client/server systems can be designed for easier use than systems with separate or stand-alone units of equipment such as receivers and spectrum analysers. With task icons and toolbars on the computer screen, which the operator can access via pointing, and clicking on a computer mouse, these systems can be very intuitive and easy to learn. For administrations with difficulty in obtaining qualified operators, simplicity of operation of a monitoring system is a very important consideration.

This section provides some examples of how spectrum monitoring equipment is operated using such visual controls and interfaces.

3.7.5.1 Scheduling and programming of automatic measurements

Automatic or scheduled mode may schedule tasks to be executed immediately or to be executed at specified times and dates in the future. Functions that are performed under the scheduled mode include technical measurement, analysis, and DF. Parameters, such as measurement and averaging methods, as well as measurement time (or times, in the case of measurements which are to be repeated) may either be specified, or pre-defined default values may be used. The operator may use a screen containing a calendar with days of the week and multiple intervals within each hour of the day to coordinate the scheduling of these functions. The client requests time slots for the desired measurements from the measurement server. The time slot assignment approach allows multiple clients to connect to a single server. In order to handle scheduling attempts of multiple measurements in the same time slot, the server should support a “convenient” mode of scheduling. When the requested time slot is already reserved, the client’s request for a server time slot is moved to the first available time slot. The server can look for the available time slot within a specified time window that is typically a few minutes. The measurement server performs the requested measurements, using appropriate scheduling and priority algorithms to resolve any scheduling conflicts, and retains the measured results until the client requests them. For some measurement types, the server may have the capacity to record signal audio along with those requested measurements.

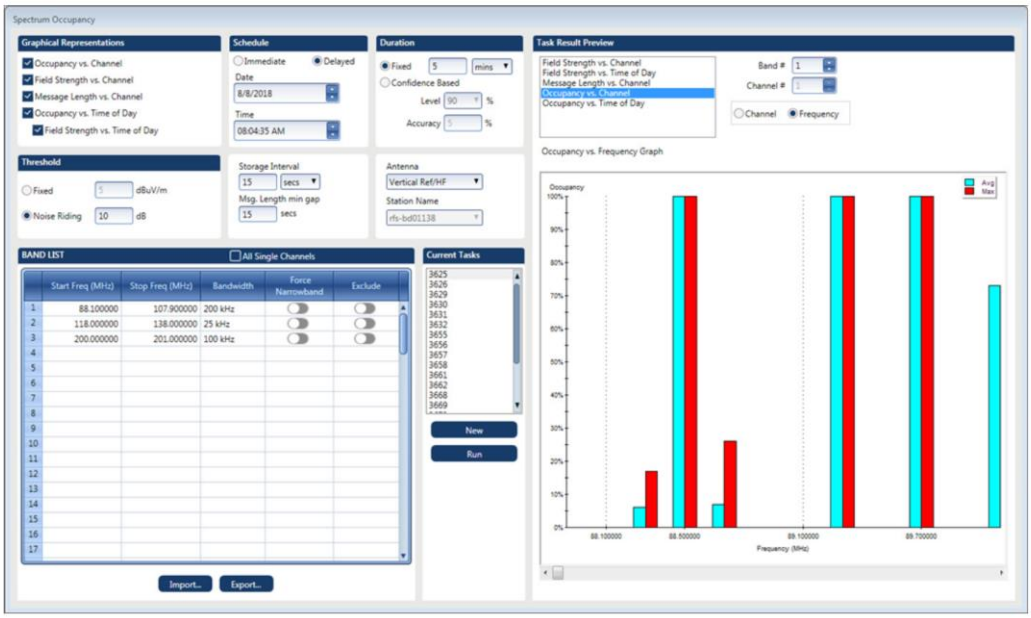
Background mode is used for performing tasks such as spectrum occupancy and automatic violation detection – tasks where it is desirable to collect data over long periods of time. Wideband scanning for occupancy, or DF combined with occupancy (termed “DF scan”), may be specified, and the system may be scheduled to perform an automatic scan over particular frequencies or ranges of frequencies, and upon detecting a signal, initiate operator specified activity, such as DF or technical measurement.

Background mode operates on a lower priority than scheduled mode. Specific scheduled measurements will interrupt the background mode to use the measurement server. After the scheduled measurements are completed, control returns to any background mode measurements that were in process.

When the client requests the results of measurements, the client may see them displayed in convenient formats. Much of the information is displayed graphically, in the form of occupancy histograms (see Fig. 3-47), field strength versus frequency plots, geographic map displays showing location results, and other graphical displays.

FIGURE 3-47

Example of occupancy histogram

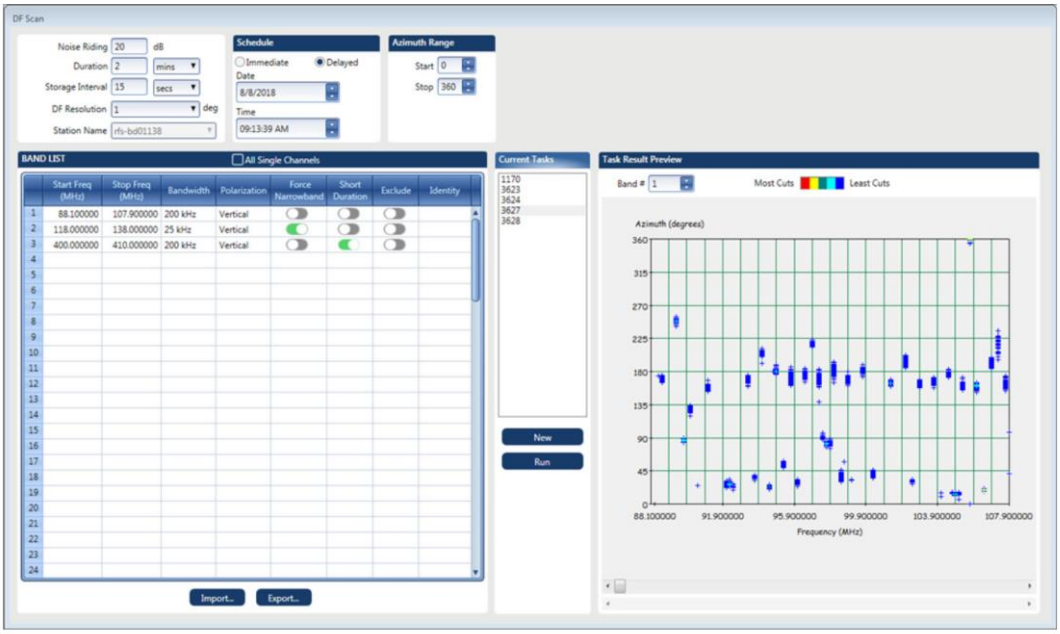


HDB-23-3-47

These systems can perform DF on many frequencies simultaneously and provide azimuth versus frequency plots (see Fig. 3-48) which are useful for intercepting and processing modern digital modulations; DF results on such a display at the same azimuth from many different frequencies are a strong indicator for the presence of a frequency hopping signal. It is recommended to compare the power level of those detected signals with the same azimuth but different frequencies to verify this assumption.

FIGURE 3-48

Example of DF scan display results



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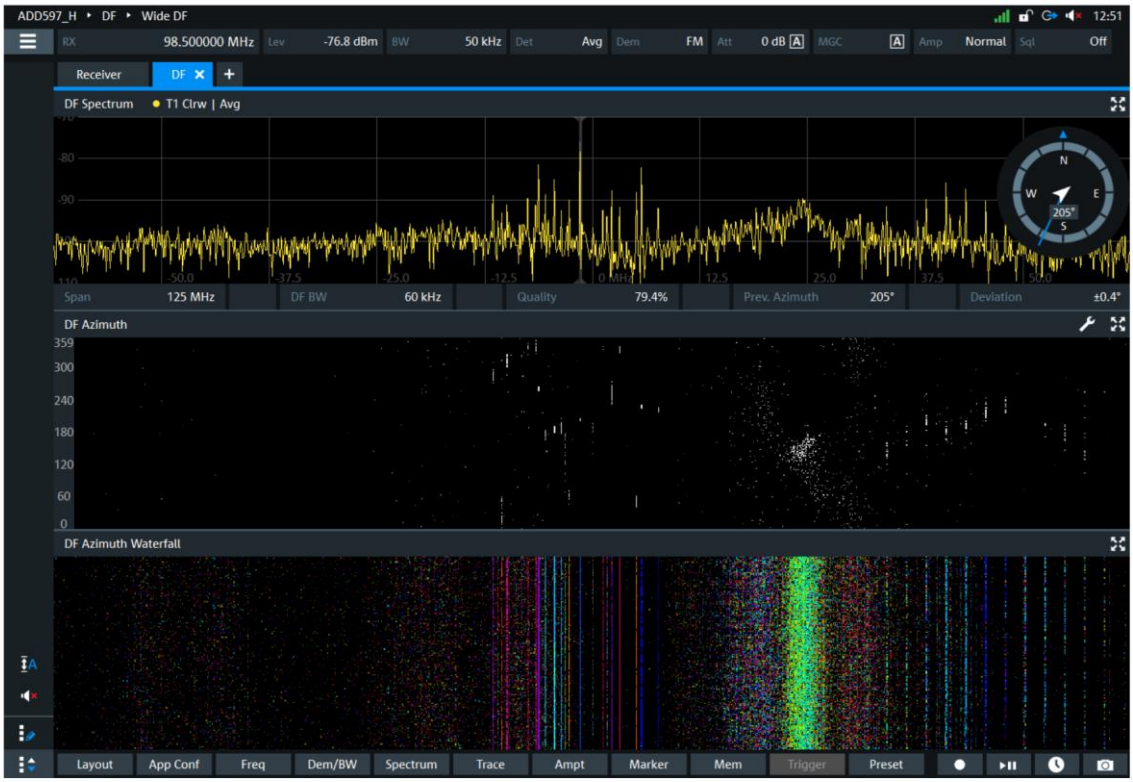
3.7.5.2 Broadband spectrum analysis

Modern DSP-based measurement servers can provide very broad instantaneous bandwidths along with a high dynamic range so that strong signals within this bandwidth do not prevent weak signals in the bandwidth from being received and processed. DSP-based systems with very broad instantaneous bandwidths can scan the spectrum at very fast rates, automatically tuning the receiver and gathering occupancy data, allowing very frequent revisits and refresh of data displays to give the operator a better understanding of the radio spectrum. They can effectively acquire and measure intermittent, broadband and frequency agile signals that may appear to be noise when monitored with a narrow bandwidth system. To provide the highest performance when narrower measurement bandwidths are desired, a smaller instantaneous bandwidth, which reduces noise and improves *S*/*N*, can be selected instead of the broader bandwidth.

Operators can view a very broad bandwidth panoramic display, improving their ability to locate interferers and identify the kinds of signals and interference being monitored. Certain systems support wideband direction finding (DF), providing a DF azimuth estimate simultaneously for every signal detected across a chosen frequency range. Figure 3-49 demonstrates a representative wideband DF display. The top portion shows the signal spectrum, with the demodulation bandwidth indicated with a grey vertical bar. The compass on the right side is referring to the selected demodulation frequency. The middle section displays DF azimuths as white dots, with brighter dots indicating stronger signals. The bottom waterfall display is colour-coded to represent DF azimuth, where colour indicates direction and intensity reflect the measured signal strength.

FIGURE 3-49

Display of wideband DF with spectrum, DF azimuth and DF azimuth waterfall

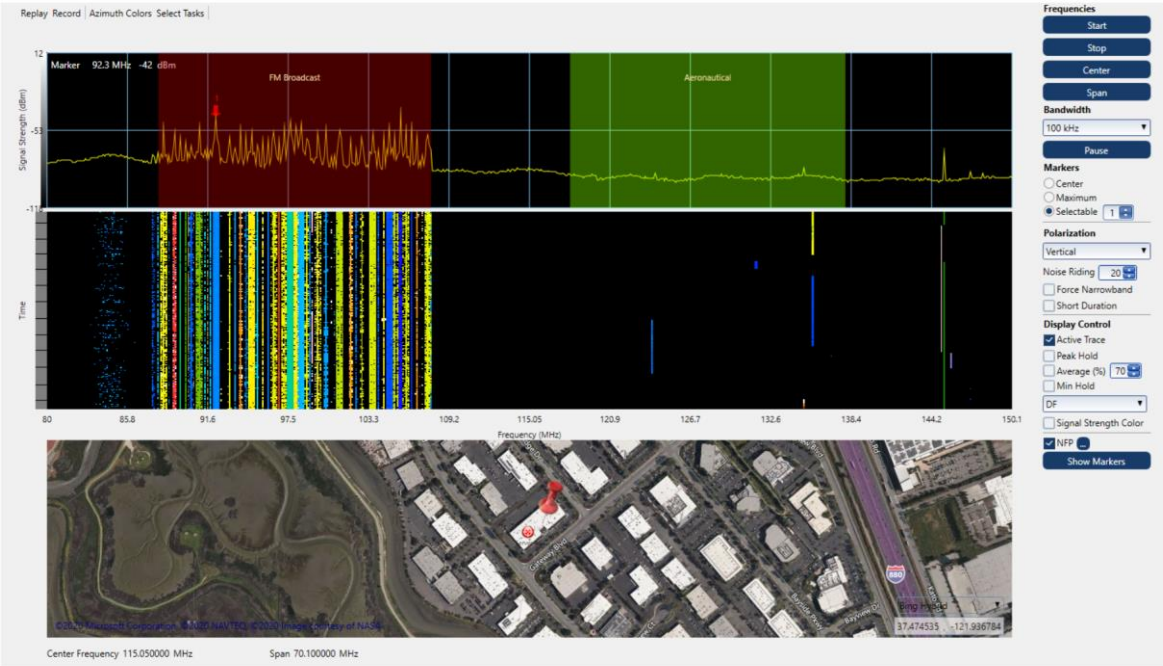


HDB-23-3-49

Another example display is illustrated in Fig. 3-50. This particular display covers over 70 MHz of the spectrum, with a panoramic display across the top of the screen, below which is a spectrogram display showing signal activity over the past 5 s, with signals colour coded as to their direction of arrival. The colour-coded direction of arrival display can be changed to a colour-coded display of signal strength upon operator command.

FIGURE 3-50

Display of very broad bandwidth measurements



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DSP allows great flexibility in adding capability to a monitoring system in the future to give it even more capability than is illustrated in the examples here. Should new signal types appear that require special processing, or new bandwidths be desired, they can be added to a DSP-based system simply by changing the monitoring system computer software.

3.7.5.3 Real-time fast spectrum scanning, instantaneous DF and operator alerts

There are certain frequency bands in which maintaining real-time control of radio transmission activity at all times is an essential requirement. This includes rapid identification and location of legal transmitters and rapid identification, location and elimination of interferers. Examples of frequency bands that require such protection are the aeronautical band, the maritime band, and various emergency channels that are essential for search and rescue operations. This type of spectrum protection requires a radio monitoring system capable of operation in real-time, with fast scanning of the spectrum and instantaneous DF measurements on all active signals. When detecting signal activity on any of the emergency channels, the system needs to be able to issue real-time alerts to local or remote operators.

Integrated signal search, DF and monitoring functions into one single processor allows fast scanning of the spectrum with simultaneous DF measurements on all detected signals. Typical systems can revisit up to several dozen maritime mobile and emergency channels at least ten times each second and can detect and measure signals as short as 10 ms.

DF results are measured simultaneously for up to several dozen channels and presented on the operator display in real-time. Lines of bearings (LOB) for selected channels are displayed on a large map and on a polar histogram. If two or more monitoring stations operate in a netted configuration (as discussed in § 4.2), then the system would display on the operator's workstation not only the LOB but also the resulting triangulation fix of the corresponding transmitter. This operation would be performed automatically by the system with no operator intervention, and the location estimate would be displayed on the operator screen within a fraction of a second after the start of transmission.

All DF measurements may be automatically stored in a local database, and retained there for a reasonable period of time such as 48 h. The operator may perform a variety of functions from his workstation computer, including:

– Monitor continuously signal activity, LOB and fixes in all his assigned channels.

– Freeze the DF results and create a transmitter location report that is automatically stored in his local database.

– Review and play back DF results and fixes stored on his computer.

– Review DF results stored on his computer and create signals activity lists.

An example of real-time operation in the maritime band with fast spectrum scanning and instantaneous DF is illustrated in Fig. 3-51. LOB is measured simultaneously for multiple channels in real-time and are displayed in numerical form on the screen (upper right). LOB for selected channels is displayed on the map (left) and on polar histogram (lower right). In this example, the operator has selected Channel 21 for monitoring, so this is the LOB shown on the map and on the polar plot. The special function keys available to the operator are shown at the top of the screen.

Figure 3-52 illustrates the case when a signal is measured by more than one radio station. In this example, there are three radio stations. The system automatically calculates the fix and displays the results on the map in real-time.

FIGURE 3-51

DF results measured simultaneously for many channels refreshed in real time (upper left); LOBs for selected channels display on map(left) and polar histogram (lower right)

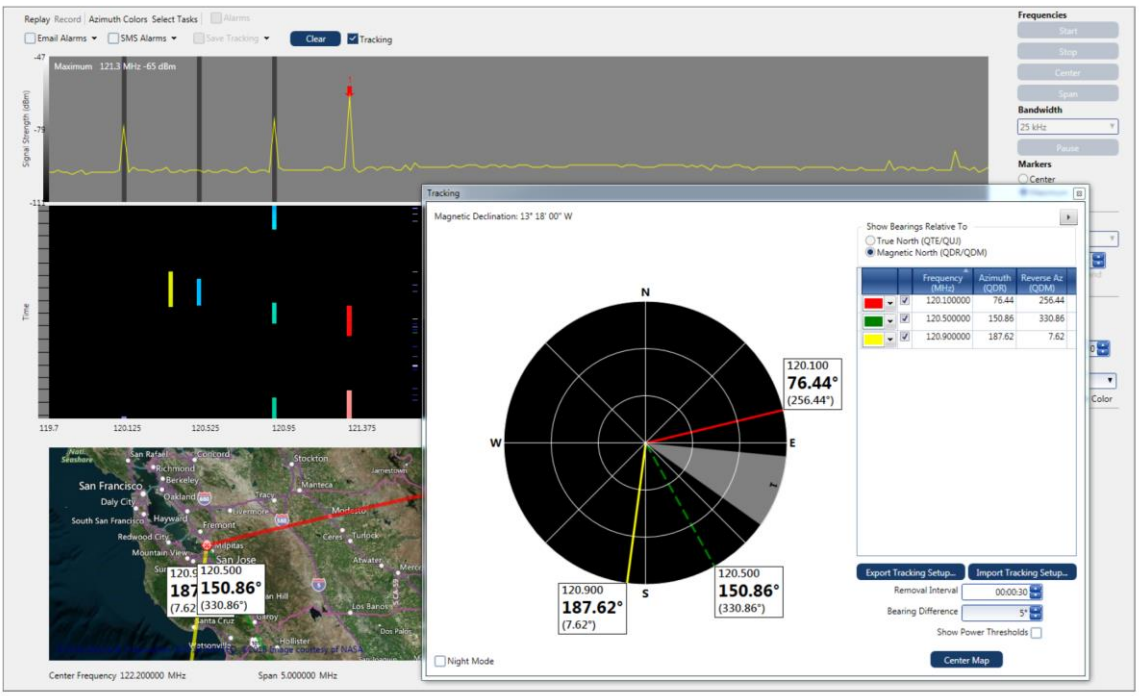

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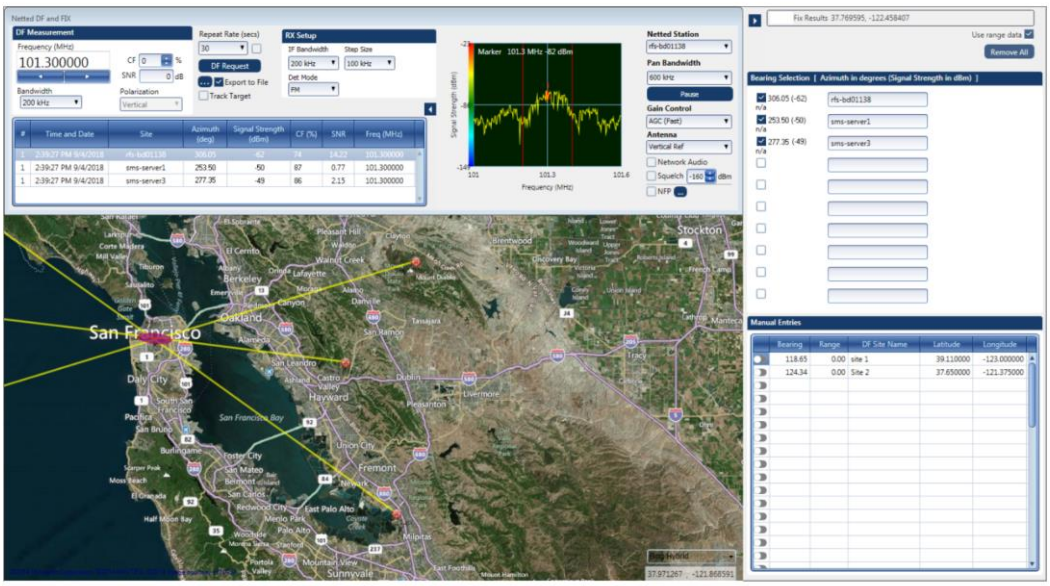
FIGURE 3-52

Display for a fix in real time, for a signal measured by more than one station



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The software may allow the operator to define several "high priority" channels. If any signal activity is detected on any of the high-priority channels, the software automatically alerts the operator on the screen, it issues an audible alarm at the workstation, and it can be scheduled to send a message to an external e-mail address or cell phone number.

3.7.6 Automatic violation detection

Spectrum occupancy measurements from a monitoring system may be compared automatically with licence information from the spectrum management system to perform Automatic Violation Detection (AVD) – to identify frequencies on which there are transmitters that are not included in the licence database and to identify transmitters that are not operating within their licensed parameters. Automatic violation detection allows the operator to define a monitored range by specifying the start and stop frequencies of the band(s) to be searched, and to specify search parameters, including the time period over which the search may be done. It is a key feature of networked, automated, integrated spectrum management and monitoring systems discussed further in Chapter 4.

The system should be able to perform a scan over the specified frequency range and for the specified time period. The system uses the measurements obtained from the scan and then uses information in the license database to determine which signals in the measured spectrum are not in the licence database, thus automatically providing a list of frequencies being used that are not in the database. The system should also check other signal parameters, such as bandwidth, over modulation deviation from licensed centre frequency, and issue alarms or reports where violations are found. Reports therefore alert the operator to unexpected or noncompliant signals based on either default criteria or on criteria that the operator has specified, and provides the basis for closer examination by the operator. Automatic violation detection results, including information on unlicensed or noncompliant transmitters by frequency or by channel, are displayed on a results screen. A geographic map display may display locations of licensed stations and indicate the locations of unlicensed or noncompliant transmitters.

In order to facilitate the automatic violation detection process and assure it is operational even in the event of unavailability of communications among stations, each client, whether at a fixed or mobile station, should maintain its own database of licensed stations in its area of operation. This database should be obtained from the management system database. With the availability of this local database, each client can continue to operate and perform automatic violation detection, even if communications are unavailable.

3.7.7 Reports in DSP-based systems

Reports in modern spectrum monitoring systems are generated with the computer software used for data analysis. These reports can be reviewed by operators and electronically made available to interested parties, either as static reports or on interactive dashboards.

Reports are focused on specific user demands, reducing the amount of information available if compared to what is presented on the equipment operation interfaces. Through reports, the reader can avoid being cluttered by data and irrelevant information and access consolidated results with the added knowledge and wisdom from operator's conclusions.

The reports may not only be based on measurements but also can draw information from various data sources, specially from spectrum monitoring historical data and spectrum management databases.

Most spectrum monitoring systems include a variety of report templates and examples, varying from very detailed presentations that may include raw trace data information, carrier analysis by date or band, channel occupancy and availability statistics, message length statistics, channel power statistics, system and alarm logs, and monitoring plan and schedule reports.

An example computer-generated report is illustrated in Fig. 3-53. The system should allow adaptation or customization of reports, according to the requirements of the operator and organization.

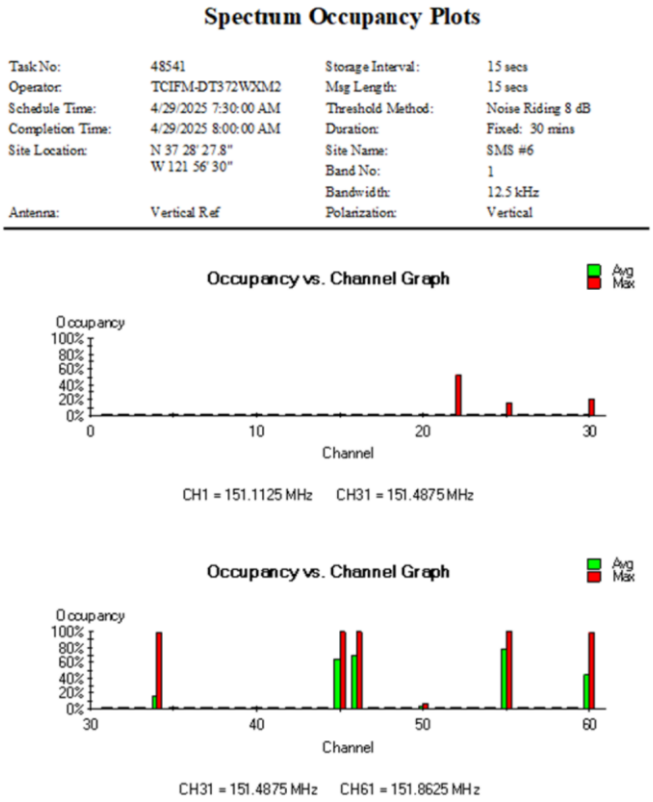
Once defined, reports may be produced automatically or manually with data from any results screen and if possible integrated into a document workflow.

Graphical reports are often a preferred method of examining data, because they provide a view of data that summarizes the information and makes it easy to identify trends and exceptions. Through the use of colour, even more information is conveyed in a single graph.

A modern system should offer the same automated report capability whether one is in a mobile unit, fixed station or management system. The capability to remotely create a report based on data that is located at a different site is also part of a typical system software.

FIGURE 3-53

Portion of an example computer-generated occupancy report



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3.8 Equipment data interface

To allow the integration and seamless operation of different elements within the spectrum monitoring system, as depicted in Fig. 3-1, the various equipment and software should share standardized common interfaces and protocols. The equipment necessary for these interfaces is described in the balance of this section.

A basic understanding of how data is transferred between different monitoring system elements is essential to comprehend possibilities and limitations of the various architectures available, thus enabling users to choose the most appropriate alternative to each use case scenario and solve simple daily problems that may arise during normal operation.

3.8.1 Data connections

As the bases for data communication modern spectrum monitoring solutions mostly employ IP networks as a *de facto* standard in the industry (as defined in the IEEE 802.3 collection). In most systems, IP networks are used to connect various components within the station itself, especially when commercial elements are integrated, such as general-purpose controller, storage and communication elements such as router and modem to provide access to the station using public or private networks. Socket TCP/IP connections may even be used within the operational system of the controller, performing inter-process communication tasks and providing API to connect application modules and software libraries.

The Internet Protocol (IP) is a package data communication technology which along with other protocols such as the TCP and UDP creates the bases by which the Internet operates.

As IP it is defined only at the network layer, it can operate over many different data links and physical mediums, from the nowadays ubiquitous SONET/SDH Fiber optics, Wi-Fi and ethernet twisted pairs cables to high-performance systems such as defined in IEEE 802.3 SR4 and SR10.

For the adequate understanding of how IP networks operate, there are numerous references promptly available over the Internet. The reader is encouraged to seek this information to grasp the integration possibilities and restrictions imposed by this technology.

Other technologies may still be found in some specific applications within spectrum monitoring systems, such as serial (e.g. USB, RS232, RS485, SFP) and parallel (e.g. IEEE488, QSFP, and system bus) but these usually do not affect daily activities since they are stable point-to-point connections.

Low speed connections still in use for communication to sensors and infrastructure automation, such as connecting to RNSS receivers, compass and power control units. Some old standards such as RS-232 with upper limit data rates of about 115 kbit/s may still be found, but mostly have been replaced by USB connections that may reach up to 80 Gbit/s (USB 4 2.0).

3.8.2 Instrument control protocols

Most spectrum monitoring solutions employ network socket communication based on TCP/IP or UDP/IP as the means to interconnect the monitoring stations, users and centralized servers.

Network sockets are logical endpoints for sending and receiving data across the network. Sockets are specific to each protocol, e.g. TCP or UDP, and are associated with a port number, which in the case of TCP and UDP may vary from 0 to 65 535 (2^{16}-1), being the first 1 024 addresses reserved as per definition of the Internet Assigned Numbers Authority (IANA).

To establish a communication, any device in the network should have the protocol to be used, IP address, and the port number of destination endpoint and define, in this process of stablishing the connection, the protocol, IP and port to be used by the other endpoint for answering.

Over the network socket level, a few different standards may be used, including proprietary protocols, that creates an Application Programming Interface (API). An API can simply be considered as interface for communication between two applications.

The use of common standards up to the API is essential to avoid vendor lock situations, which may increase maintenance and replacement costs to administrations and limit the capability of integrating any multi-vendor software solutions.

Some of the key existing solutions are described in the following subsections.

3.8.2.1 VISA/SCPI

Virtual Instrument Software Architecture (VISA) is the most widely used API for measurement instruments and is currently maintained by the IVI Foundation, an open consortium supported by several of the most prestigious instrument manufacturers, currently including 19 members.

The VISA specifies communication requirements over different media layers, including GPIB, VXI, USB (USBTMC) and most importantly TCP/IP (HiSLIP or VXI-11) and several libraries are available that allows easy integration with different software platforms and architectures.

Due to the ample availability of libraries that allows the integration of VISA communication into most programming environments, it is not necessary to further describe the underlying structure of this protocol but is important to understand its limitations.

VISA provide only low-level compatibility. To be able to interchange equipment from different manufacturers, it is not only essential that they are functionally equivalent and provide a VISA interface, but also that both equipment share a common application layer structure. Thus, come into play the Standard Commands for Programmable Instruments (SCPI) standard.

The SCPI was originally designed in 1990 as a standard for syntax and commands to be used on top of the GPIB (IEEE-488) interface. Later it was naturally adopted as a general syntax guide for newer interfaces, including VISA, creating what is commonly referred to as VISA/SCPI stack.

SCPI commands are defined in text format using ASCII code to define keywords and associated parameters when necessary. Response data is typically defined also in ASCII, although binary data can be used for transmission of bulk information, such as spectrum sweeps or I/Q data.

Although the VISA/SCPI stack do provide a common basis, still there are many specific configurations that are not fully defined in these standards, mostly because different hardware may require different setup procedures and it is not uncommon to see that different models of equipment from a single manufacturer may require different preset configurations before a certain default measurement command may be issued.

Such variability implies that multi-vendor application should include ways to swiftly create functional dictionaries that enable to create different sequencies of commands to attain comparable results from different equipment models. This may be accomplished by expertise users with proper training or may require additional service support from the software vendor itself, an aspect that should be considered when planning for the use and maintenance of such software.

3.8.2.2 VITA-49 and DIFI

While VISA/SCPI are non-specific and more generally employed by all kinds of instrument interface, there are some standards more focused on the interoperability within radio frequency data acquisition systems and thus deserve some highlight in this Handbook.

VITA-49, formally known as the *VITA Radio Transport (VRT) standard*, was developed by the VMEbus International Trade Association (VITA). It defines a standardized packet-based framework for transporting digitized radio signals and associated metadata over high-speed digital interfaces. VITA-49 is specified in ANSI/VITA 49.x standard family and is primarily designed for real-time streaming of baseband I/Q data, spectral data, and control information. It is widely adopted in military, aerospace, and high-performance test and measurement systems, as well as in commercial SDR platforms and modular instrumentation products. Its principal strength lies in enabling interoperability between digitizers, receivers, processors, and recorders from different vendors within real-time systems.

DIFI (Digital IF Interoperability) builds upon the VITA-49 framework and is specified by the Digital Intermediate Frequency Interoperability (DIFI) Consortium. DIFI defines a constrained profile of VITA-49, including standardized packet types, metadata fields, and usage conventions, with the objective of improving interoperability and reducing ambiguity in the exchange of digitized intermediate-frequency (IF) and baseband data. DIFI is primarily targeted at high-end critical systems where open architectures and multi-vendor interoperability are essential.

3.8.2.3 NMEA

The acronym NMEA refers to the United States based trade organization National Marine Electronics Association (NMEA) and is used as reference to the standards published by that organization which defines characteristics for data communication between marine electronics.

Most importantly for the spectrum monitoring use case, this includes devices such as radionavigation-satellite service (RNSS) receivers and compass that are adherent to the NMEA 0183 standard or its successor, the NMEA 2000, abbreviated to NMEA2k or N2K. This latest standard is also standardized by the Working Group (WG) 6 of Technical Committee 80 (TC80) of the IEC as the IEC 61162-3.

NMEA use ASCII serial characters in the form of specific sentences including information such as: indication if a RNSS satellite fix is attained, the resulting latitude and longitude, UTC date and time, number of satellites in view, quality of the result, ground speed, among others.

Some spectrum monitoring equipment may provide full access to raw NMEA messages, allowing to improved identification of operational conditions that may affect the spectrum monitoring activities due to unreliable RNSS or Compass information.

3.8.2.4 Vendor specific protocols

The use and integration of equipment that uses vendor-specific protocols into a multi-vendor spectrum monitoring network environment might be as easy as with those that employ a public or open standard, such as those already mentioned, but a few conditions should be observed when considering the use of this type of protocol and requirements applicable to allow later integration.

A common scenario is that the vendor specific protocol is fully documented, and its use may be licensed to the administration or a third-party software vendor/integrator, which will then be responsible for developing the interface to existing systems.

Another alternative is that the vendor provides precompiled binaries that exposes open interfaces that can be used to integrate the equipment into the existing spectrum monitoring network.

In both cases, to avoid difficulties in acceptance tests and later integration work, it is important that the vendor also provides a companion Software Development Kit (SDK), including documentation and fully functional examples with code that can be used by the administration or assigned integrators to test and understand the provided software and information.

Considering both alternatives indicated, having access to the manufacturer protocol specification is the most flexible and desirable option, since it allows the integration of the equipment using state-of-the-art technology, targeted to the desired Operational System (OS) environment and architecture (x86, x64, ARM, etc).

Using precompiled binaries will require the specification of OS and architecture as part of the purchase and license process and will limit the alternatives for development environments to be used. Pre-compiled binaries may also require additional libraries with further licensing costs.

Access to support services during integration process is essential, even more so in the case of use of precompiled binaries. It is not uncommon for documentation to be lacking in detail that are hard to pinpoint at an initial evaluation but may turn out to be critical for the later integration of the solution and bugs in the provided binaries are likely to be identified, which may require complementary documentation, software patches and new releases.

3.8.3 Controller host access and data transfer

3.8.3.1 Remote access to monitoring stations

Although most solutions include client software to enable remote operation of the monitoring station (using protocols as described in the previous section), direct access to the monitoring station desktop or command line interface is often required for configuration and maintenance purposes. It is to be noted that remote access may be disabled for security/sovereignty reasons. A physical operation and air-gapped architectures can also be acceptable operating models in such cases.

Such remote access may also be desirable to enable the use of the monitoring station by multiple users, without requiring the use of specialized client software installed on the user machine, or to take benefit from the reduced delay and larger data communication bandwidth within the station to allow for more advanced data processing, such as using I/Q Data.

The remote access protocol will depend on the Operational System (OS) in use by the station controller. Most commonly, monitoring stations employ Windows OS, which will use Remote Desktop Protocol (RDP), a proprietary format from Microsoft that is publicly available.

Other common alternative used is Linux OS, in which case the *de facto* standard for remote access is through Command Line Interface (CLI) via Secure Shell Protocol (SSH Protocol).

SSH is part of the OpenSSH suite and is available for several operating systems, including Windows. OpenSSH also includes other tools, most notably, the Secure File Transfer Protocol (SFTP), which may be used for file transfers over a secure encrypted channel.

Although most remote access services are defined with default protocols and ports, e.g. TCP or UDP at port 3389 for RDP; TCP, UDP or SCTP port 22 for SSH, these default configurations may be changed due to Network Address Translation (NAT), port forwarding, proxy and firewall configurations. Such nonstandard configurations are not an issue *per se* but may be confusing if not properly documented.

Finally, another form of remote access is through a web interface. In simple terms, the monitoring station incorporates a web server that provides access functions and services such as the configuration of the receiver settings, programming of automatic measurements, and visualization of the results through an HTTP page. Such interfaces may be accessed by users through a common web browser and, with the aid of modern JavaScript components, may be able to render graphical items with comparable quality to classical desktop applications.

3.8.3.2 Data transfer for automated operation

When considering the communication between monitoring stations or between stations and a central automation server, it is desirable to have a more structured data exchange method than that provided by the standard user interface and simple remote access.

There a few methods for data exchange used by spectrum monitoring solutions; common alternatives include: the use of files; the use a TCP/IP API (e.g. socket communication as discussed in § 3.8.2); or through in-system API (e.g. using pre-compiled binary libraries – DLL).

For example, pre-defined measurement script files can be submitted to the monitoring station controller, which in return produces data files that may be later accessed by the application that requested the measurement. This establishes an asynchronous operation mode suitable for continuous operation, performing tasks such as the collection of long-term occupancy data or the monitoring of critical bands for early identification of interference sources, and the issuing of pre-emptive alerts.

File transfer operations may be performed using Secure File Transfer Protocol (SFTP) or other methods, including commercial cloud-based solutions for file mirroring, backup and synchronization.

Defining the technology to be used should consider aspects such as the volume of data to be transferred, the ability to manage the file transfer process, security and the underlying data network infrastructure, its capacity and reliability.

The ability to manage the file transfer process is a key aspect to consider when deploying the spectrum monitoring network. Simple synchronization tools will not allow files to be updated in either of the synchronized folders, which may compromise the overall system operation. For example, when raw measurement results are be loaded into a repository or database resulting in a file name and location different from the original synchronized folder, a simple synchronization tool will not be able to track the change and may cause a file to be copied multiple times or require the repositories to be kept in specific modes that are less reliable or less efficient in the management of the overall storage capacity.

Also, depending on the number of stations, and individual storage capacity at each site, the total capacity required in a central repository may be too large to be economically acceptable if a full synchronization from all stations is performed. However, this limitation can be greatly minimized through the use of edge computing, which allows preliminary data processing, compression, and summarization to occur locally, at each monitoring station.

By transmitting only the essential analytical results and metadata to the central repository, the overall network load is reduced, making it feasible to connect a larger number of sensors and expand the network's coverage without proportional increases in storage or bandwidth requirements.

At the same time, being able to address measurement files across multiple locations enables an efficient use of the network's total storage capacity, maintaining a central storage with mostly summarized data while preserving the ability to retrieve raw information from remote sites when required.

An alternative to the use of files is the use of services, either provided by the monitoring station to users and other services or provided by central servers to the monitoring stations.

The use of services enables the synchronous operation of the network components, avoiding the risk of using outdated information for data analysis, being especially useful for real-time and critical operations.

Services may use a variety of network socket communication formats, such as described in § 3.8.2, but it is increasingly common to use standardized services based on HTTP, with an architectural style known as REST (Representational State Transfer) and RESTfull. For low latency, flexibility or high-performance applications, other standards, such as: gRPC (Protobuf), WebSockets, GraphQL can be found on available spectrum monitoring solutions.

Providing a standardized architecture such as defined by the standards described above reduces the costs of integration between systems, enabling the reuse of software libraries, frameworks and allowing the use of improved security mechanisms, among other features.

3.8.3.3 Audiovisual streaming

Apart from equipment control and measurements, a common activity in spectrum monitoring is the demodulation of audio, video and data content for the purpose of emission identification or other regulatory enforcement purpose. This may be required in many cases when there is no digital identification code being transmitter (e.g. RDS) or such identification is under question.

For this task, most monitoring equipment do provide means of demodulation and streaming of the emission content in the form of audio, video and data streams.

Usually, the transmission of raw I/Q data or non-compressed audio and video basebands is not feasible due to restrictions in the transmission rate achievable, specially across large areas. Thus, monitoring station are usually equipped with demodulators and encoders capable of efficiently use the available data transmission medium to stream the demodulated information over IP networks using lossy compressed formats.

A desirable approach for streaming is to use common protocols such as HTTP Live Streaming (HLS), described in RFC 8216 (Pantos and May, 2017), Real-time Transport Protocol (RTP/RTCP), described in RFC 3550 (Schulzrinne *et al.*, 2003) or Faster Than Light (FTL) protocol and MPEG-Dash.

An important aspect to consider about the use of compression methods is the delay and response time and the impact to the user experience. Protocols like HLS imposes delays in the order of 10 to 30 seconds, RTP and Web Real-Time Communication (WebRTC) usually keep delay in the order of 2 to 5 seconds, while FTL can keep delay in the order of few hundreds of milliseconds.

These protocols create the basis of modern web audiovisual applications, providing high-quality compressed audiovisual content.

To reduce complexity and the problems associated with delay, it is not uncommon to find spectrum monitoring solutions that stream demodulated data using simple linear pulse-code modulation (LPCM) encoding without compression, or employ protocols normally used for interactive voice and video conferencing, which may cause other use restrictions. In regards of latency and firewall hurdles, uncompressed or lightly compressed audio, such as pulse-code modulation (PCM) and store-and-retrieve workflows may be preferred over interactive live streams, on some use case scenarios.

Apart from the concern about the required transmission rate, some protocols like RTP still use UDP for the underlying communication, which may result in difficulties to transverse firewalls and NAT barriers.

All these limitations should be considered when deploying spectrum monitoring solutions, since they may affect the possible choices of network architecture, underlying network service costs, and the user experience.

References

ITU-R Recommendations and Reports

NOTE – In every case, the latest edition of the Recommendation is encouraged to be used.

Recommendation ITU-R F.162 – *Use of directional transmitting antennas in the fixed service operating in bands below about 30 MHz*

Recommendation ITU-R BS.705 – *HF transmitting and receiving antennas characteristics and diagrams*

Recommendation ITU-R SM.331 – *Noise and sensitivity of receivers*

Recommendation ITU-R SM.332 – *Selectivity of receivers*

Recommendation ITU-R SM.1836 – *Test procedure for measuring the properties of the IF filter of radio monitoring receivers*

Recommendation ITU-R SM.1837 – *Test procedure for measuring the 3rd order intercept point (IP_3) level of radio monitoring receivers*

Recommendation ITU-R SM.1838 – *Test procedure for measuring the noise figure of radio monitoring receivers*

Recommendation ITU-R SM.1839 – *Test procedure for measuring the scanning speed of radio monitoring receivers*

Recommendation ITU-R SM.1840 – *Test procedure for measuring the sensitivity of radio monitoring receivers using analogue-modulated signals*

Recommendation ITU-R SM.1050 – *Tasks of a monitoring service*

Recommendation ITU-R SM.1370 – *Design guidelines for developing advanced automated spectrum management systems*

Recommendation ITU-R SM.1537 – *Automation and integration of spectrum monitoring systems with automated spectrum management*

Recommendation ITU-R SM.2060 – *Test procedure for measuring direction finder accuracy*

Recommendation ITU-R SM.2096 – *Test procedure for measuring direction finder sensitivity in the VHF/UHF frequency range*

Recommendation ITU-R SM.2097 – *On-site accuracy measurements of a fixed direction finder system*

Recommendation ITU-R SM.2140 – *Performance evaluation of mobile direction finders in operational environment*.

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CHAPTER 4

Data management, automation and networking

TABLE OF CONTENTS

Page

4.1 Introduction to data management and automation 176
4.1.1 Data lifecycle 176
4.1.2 Analytical capability and automation 177
4.1.3 Chapter organization 179
4.2 Spectrum monitoring network 180
4.2.1 Core spectrum monitoring network elements 182
4.2.2 Spectrum monitoring network management 185
4.2.3 General spectrum monitoring network architecture and cloud services 188
4.3 Data collection 190
4.3.1 Spectrum monitoring data collection 191
4.3.2 Manual data collection 191
4.3.3 Automated data collection process 191
4.4 Store, publish, archive, reuse and delete 193
4.4.1 Data formats 193
4.4.2 Data transfer and storage 196
4.4.3 Data management 198
4.5 Process and analysis 200
4.5.1 Signal conditioning and structuring 201
4.5.2 Intelligent analysis and inference 203
4.5.3 Application of ML techniques in Radio Monitoring 209
4.6 Data usage and intelligent interaction 218
4.6.1 Human–machine interaction and usability standards 218
4.6.2 Visualization and decision support 220
4.6.3 AI-augmented data usage 223
4.6.4 Human–AI collaboration and future directions 226
4.7 References 227

4.1 Introduction to data management and automation

This Chapter focuses on the data management and associated processing tasks, starting from the automation of spectrum monitoring data acquisition, throughout the data lifecycle until discarding and storage policies. It also describes networking as a vehicle to control tasking, transport the various forms of spectrum monitoring data, as well as methods and techniques for network management and security.

The proposal for this Chapter came from the recognition that the capabilities of modern receivers and spectrum analysers, in terms of the large data collection and processing, can only be fully explored by advanced automation and data management techniques, that thus stands with greater importance within the spectrum monitoring process and requires a more detailed review within the Spectrum Monitoring Handbook.

4.1.1 Data lifecycle

This Chapter explores the pivotal roles that automation and data management play in establishing, operating, and maintaining an effective national spectrum monitoring service, from local measurement and processing to cloud-level fusion, analysis, and reporting, laying the foundation for next-generation monitoring systems, as envisioned in Report ITU-R SM.2542.

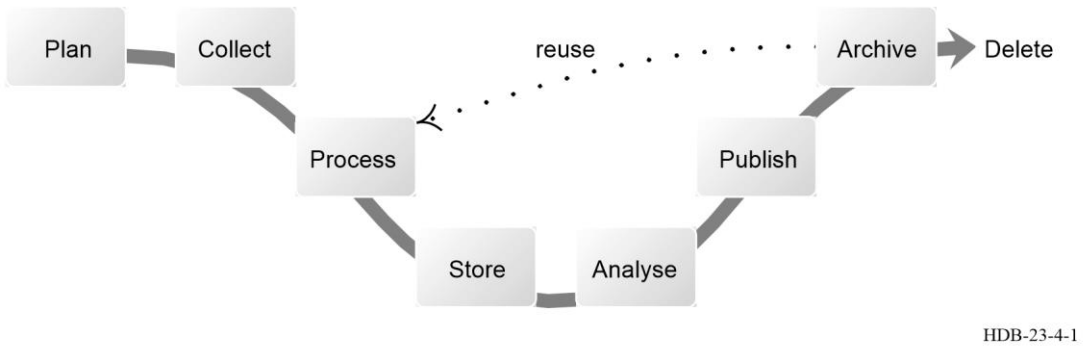
To fully understand the concepts herein described, it is essential to revisit the foundational principles of data management systems.

Data storage and processing have evolved remarkably from the earliest forms of communication to modern digital formats, but some essential aspects have been retained in all formats and can be understood in the framework of data lifecycle models.

While numerous models exist in the literature [Bose & Marijan, 2023; Durango *et al.*, 2024; Faundeen *et al.*, 2013; D. Zhang *et al.*, 2023], this chapter organization employs the lifecycle model depicted in Fig. 4-1, illustrating the phases from planning the measurement tasks and spectrum data collection, through processing, storage, analysis, visualization, publication, sharing, archival and deletion.

FIGURE 4-1

A simplified general model for data lifecycle



This chapter provides an overview of spectrum monitoring activities aligned with the data lifecycle, sometimes drawing connections to other chapters in this Handbook and other ITU documents. For example, Chapter 2 describes how spectrum monitoring services are organized. For a deeper understanding about the tools used for data collection, the reader may refer to Chapter 3, which also describes data processing, storage and analysis. Further details on processing and analysis as measurement methods are found in Chapter 5 and specialized monitoring systems are described in Chapter 6. Various technologies used to plan, deploy and operate a spectrum monitoring network are described in Chapter 7.

4.1.2 Analytical capability and automation

Traditionally, automation was referred to as the process of replacing human intervention on repetitive tasks, which in the scope of spectrum monitoring, was translated as performing scheduled data capture tasks in off-hours and during extended periods of time. Such basic tasks also include the deployment of software updates, file transfers to/from remote stations, and infrastructure maintenance.

However, recent developments in data processing have brought profound changes to the role of automation in spectrum monitoring. Further advancements in Artificial Intelligence (AI) and Machine Learning (ML) are expected to be even more momentous, altering the tasks and roles of human agents in the spectrum management process.

This Chapter describes the traditional automation processes related to data collection and storage, which remain the most common and foundational features in all spectrum monitoring solutions. It also considers the expanded role of automation across the other phases of the data lifecycle (data processing, analysis, validation and reporting) as part of the transition toward continuous and intelligent monitoring frameworks. This broader role of automation may be understood as an act of delegating tasks to machines where the extent of delegation depends directly on the analytical capability of the system.

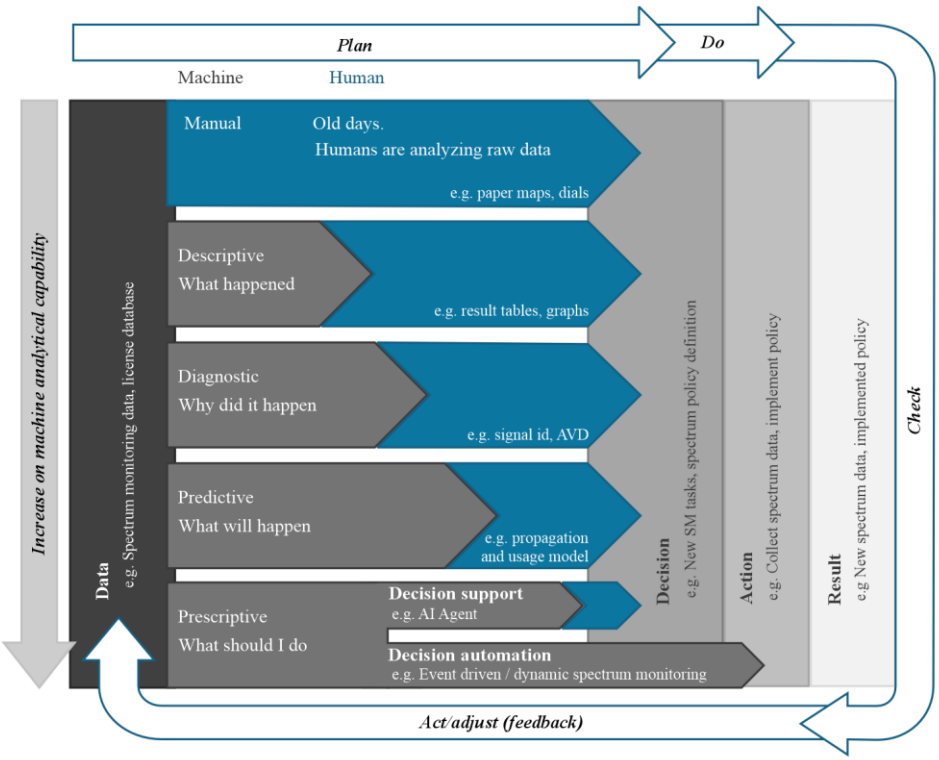
In conventional monitoring operations, automation focused on repetitive or scheduled actions, such as routine measurements, file transfers, and data storage. In contrast, as presented in Report ITU-R SM.2542, next-generation systems employ automation as a core operating principle, extending their scope to include features such as edge processing, cloud-based data fusion, and AI-assisted decision support.

Modern platforms following this model can perform continuous signal acquisition, real-time validation of spectrum occupancy, and automatic cross-correlation of measurements with authorized emission databases and simulation models. Through machine learning and predictive analytics, they can autonomously identify anomalies, classify non-compliant signals, and generate intelligent reports that summarize technical findings for regulatory decision-making. In this way, automation no longer serves merely to facilitate operations – it becomes a central mechanism of regulatory intelligence, transforming raw monitoring data into actionable knowledge.

When viewed in the Plan, Do, Check, Act (PDCA) process control framework, automation enables a progressive redistribution of roles between humans and machines. As the analytical capabilities of systems increase, machines can assume greater responsibility for the Do and Check phases – executing measurements, validating results, and even initiating corrective actions – while human operators focus on strategic oversight, policy enforcement, and long-term planning. This evolution is illustrated in Fig. 4-2 (based on [Rivera & Meulen, 2014]) which shows how (in the context of PDCA) the balance between human and machine roles shifts as analytical capability advances, paving the way for fully autonomous monitoring ecosystems.

FIGURE 4-2

Levels of analytic capability



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The vertical axis represents increasing analytical capacity of machines, while the horizontal axis reflects the shared and shifting roles of humans and automated systems throughout the decision cycle. At the initial stages (manual and descriptive), operators interpret raw data and create analytical summaries manually.

As monitoring systems evolve, diagnostic and predictive analytics begin to rely on machine-learning algorithms capable of identifying signals, estimating coverage and occupancy, and correlating observations with authorized frequency assignments. In the prescriptive stage, artificial-intelligence agents and decision automation mechanisms generate real-time recommendations or enforcement actions, creating a closed operational feedback loop.

Modern monitoring architectures embody this evolution in practice. Local sensors perform continuous measurement and on-site analytical processing, determining channel occupancy, bandwidth, and extracting signal parameters before transmitting compressed results to data repositories. Monitoring results can be integrated by the Spectrum Management System which performs large-scale spatial analysis and automatically generates intelligent reports that support decision-making.

At the upper tiers of the analytical-capability curve – predictive and prescriptive analysis, data not only describes the spectrum environment but can initiate actions and define what should be monitored to improve existing spectrum usage models. It can also suggest enforcement or regulatory actions that may address high-level strategic goals.

This forms the foundation of next-generation monitoring systems, enabling administrations to transition from event-driven monitoring to continuous, proactive, and autonomous spectrum governance. It ensures that every stage of data processing not only feeds the next but also enhances the overall intelligence of the system, creating a closed feedback cycle that supports sustainable, data-centric regulation.

As monitoring systems evolve toward continuous, data-driven and autonomous operation, the concept of a digital twin may emerge as a natural extension of the described architecture. In this context, a digital twin can be understood as a dynamic virtual representation of the monitoring network and its environment, continuously

updated through integration of real-time and historical data, and capable of supporting simulation, prediction and decision-making processes [Abdelrahman *et al.*, 2025; Liu *et al.*, 2021]. For fixed spectrum monitoring networks, this approach could enable advanced functionalities such as predictive assessment of spectrum usage, simulation of interference scenarios, and optimization of monitoring strategies through closed-loop interaction between physical infrastructure and analytical models. While still an emerging concept within the spectrum monitoring domain, digital twins illustrate a possible direction for deeper integration between data management, automation and intelligent analysis. In this modern configuration, data circulation becomes continuous and bidirectional: measurement stations act as autonomous producers of validated information, while the cloud aggregates, correlates, and redistributes insights to guide operational and regulatory decisions.

By overcoming the isolation of vendor-specific systems through synchronization and open data exchange, administrations can leverage their existing infrastructure while achieving a unified, data-driven monitoring environment.

As of this publication, the use of advanced analytics (including AI) within spectrum monitoring services is still in its infancy but is rapidly developing. In this context, the present chapter is a dated picture of the state of art, presenting available solutions, references and prospective scenarios that may be used by the spectrum monitoring community in the coming years.

This Handbook does not recommend the adoption of any specific technology. It is essential that organizations using these technologies evaluate carefully the expected risks and opportunities prior to adoption.

4.1.3 Chapter organization

This Chapter is organized in the following sections:

– Section 4.2 presents essential elements of the spectrum monitoring network, describing core components and communication layers, including local (LAN) and wide-area (WAN) connectivity. It discusses network management aspects such as cybersecurity, observability and configuration management, and presents architectural approaches ranging from local and centralized deployments to distributed and cloud-based models, including edge computing paradigms and serverless infrastructures.

– Section 4.3 addresses the data collection phase. It examines both manual and automated data acquisition processes extending the concepts already presented in the previous chapter, including scheduling, trigger-based monitoring, event-driven monitoring (EDM), and dynamic spectrum monitoring (DSM). The section highlights the implications of automation for resource allocation and system sustainability.

– Section 4.4 addresses the subsequent stages of data handling: storage, publication, archiving, reuse, and deletion. It presents considerations on data formats, metadata, cataloguing, and data-sharing practices, as well as discard strategies that balance operational needs, regulatory requirements, and long-term usability with references to ITU-standardized structures and open formats.

– Section 4.5 examines data processing and analysis. It first details signal processing stages such as formatting, detection, segmentation, and feature extraction. It then introduces intelligent analysis techniques, including machine learning and deep learning approaches, highlighting applications such as clustering, classification, anomaly detection, and prediction. Classical analytical methods are described in further detail in Chapter 5.

– Section 4.6 focuses on data usage, with initial emphasis on user interfaces, controls, and visualization tools, including a review of usability standards. It extends the discussion of data usage by considering human–machine collaboration, the integration of AI and brain-inspired intelligence, and approaches based on large language models, such as Retrieval-Augmented Generation, and Reason-and-Act. The section also outlines open challenges and directions for further work.

– Section 4.7 provides references and a list of abbreviations is provided in this Handbook to support the technical concepts presented throughout the chapter.

As these concepts are presented, specific technological solutions may be used as examples, but not as recommendations. The reader should take a critical view of these examples in accordance with their own context, technical capabilities, and requirements.

4.2 Spectrum monitoring network

To better understand how data is managed and used within the spectrum monitoring process, it is important to have some general understanding about how the spectrum monitoring network is organized and review some of the key concepts associated with network architectures and technologies. Such knowledge is also critical when planning and deploying these networks, since it may have significant impact on operational costs and performance.

A spectrum monitoring network may consist of several attended and unattended fixed and mobile monitoring stations, each following the general descriptions presented in Chapter 3, including features in accordance with its intended use.

Networks improve overall system efficiency by providing fast data communication and operations between remote locations, enabling tasks such as automated emitter location, with associated benefits of better use of human resources. It permits administrations to be proactive in the protection of critical spectrum resources and to better manage equipment availability and security.

Transmission of data within and between network nodes, e.g. monitoring stations, clients, servers, usually have the following characteristics:

– Internal to the monitoring station, components usually employ data rates compatible with the service requirements, e.g. few hundred bytes per second for RNSS receivers or compass modules, multi gigabyte per second for I/Q data between digitizer and processor. Usually, these transfer rates are not relevant for routine spectrum monitoring network operation and might be even inaccessible to users.

– From the monitoring stations to the control centre, essential information such as bearings and field-strength levels can be transmitted using low data rate. Higher data rates are required for the transmission of more complex data, such as spectral traces, audio, video, remote desktop access, raw I/Q or spectral data, and the transfer of large files.

– From the control centre to the monitoring stations, assignments, instructions for synchronised measurements such as direction finders or TDOA, responses to requests of the centre's database and service information are transmitted. Typically, each control centre will generate low data rate communications towards each monitoring station, but higher capacity may be required.

– Between distributed regional control centres and centralized servers, data from local databases and service information may be exchanged which may result in high data rates, especially if multiple stations are routed through a common network node, such as for centralized backup operations. Since control centres are usually within the administration offices, additional bandwidth is required for general administrative purposes, such as digital document services, electronic mail, instant messaging or online meetings.

The above list makes it evident that, in terms of required data rate, traffic between monitoring stations is often asymmetrical. Monitoring stations may be viewed as server nodes of the network, providing a set of very specialized services with high output and low input. Control centres usually place the highest demand on the bandwidth in the other direction, consuming data from multiple monitoring stations. Table 4-1 lists some typical applications used in spectrum monitoring networks and the associated data rates.

TABLE 4-1

Typical data rates used in spectrum monitoring networks

Type of data transferred	Typical data rates	Example
Commands to/from the control centre to a station Single measurement results including DF	Few kbit/s	VISA/SCPI commands to setup a spectrum analyser with 186 bytes: "DISPlay:WINDow:TRACe1:MODE AVER;:SWEep:COUNt 3;:DETector1:FUNCtion RMS;:UNIT:POWer DBM;:FREQuency:STARt 76000000;:FREQuency:STOP 108000000;:SWEep:POINTS 1001;:BANDwidth:RESolution 100000" The answer to this command, with a trace data of 1001 points, would take 2009 bytes, including 6 bytes for header, 1 for termination and 2002 data bytes using a representation as float16.
Spectrum sweeps (live spectra) Multiple/sequential measurements, including DF	Up to 64 kbit/s	Visual spectrum representation with HD resolution (2^{11}) and 0.5 db accuracy (8-bit depth), with 250 ms refresh rate, can be achieved with 65 kbit/s, without compression. Compression of 10 times or more are achievable with simple lossless methods.
Demodulated audio (narrowband) or Compressed I/Q measurements (TDOA)	Up to 128 kbit/s	AAC or MP3 audio codecs provide medium quality with 128 kbit/s for audio sample rate up to 48 kHz. Even at low-quality configuration, with half of this rate, audio is usable for monitoring purposes.
Remote computer control (transfer of screen contents with interactivity, with compression (no video playback)	Up to 1 Mbit/s	Recommended Remote Desktop Protocol (RDP) bandwidth requirements.
Remote computer control with live video playback Wideband raw spectrum information (I/Q data)	More than 1 Mbit/s May require several Gbit/s	25 kHz BW with 12-bit sample depth requires about 600 kbit/s for I/Q data transmission (1 Hz resolution without compression)

Values given in the Table above are illustrative and large variations may be expected depending on the measurement equipment characteristics (bandwidth, sample rate, sample size, raw bitrate per sample, response time), software implementations (applied data summarization, compression, protocol efficiency), and usage conditions (e.g. scan of large or multiple bandwidths, multiple simultaneous audio streams from a wideband receiver with DDC and SDR features, wideband I/Q data transmission).

The indicated data rates can also be used as reference for offline and automated operation, in which case, the size of produced files will be equivalent to the product of the expected data rate and the acquisition time. Note that the resulting files may be hundreds of MB or GB in size per hour, which may impose requirements on the telecommunication service agreements for the data links to be used, e.g. bitrate bandwidth and monthly data usage limits.

The choice of the network architecture and data link depends on the volume of data to be transferred, expected response time, existing network infrastructure, sovereignty and security issues and should consider the availability and quality of service agreements that need to be established.

In general terms, networks based on IMT-Advanced (4G) and beyond or commercial satellite services can be used to remotely operate spectrum monitoring stations for most scenarios. However, the use of fixed network connections, either private or through the internet using Virtual Private Network (VPN) or similar technologies are desirable for their reliability.

Constrained links conditions may be overcome by limiting transfers to summarized metrics (e.g. averaged levels, occupancy statistics) and event driven file uploads. Live audio, spectrum data or I/Q streams can be considered optional monitoring tasks and even offline operations can be useful to collect long term data under restrictive conditions.

4.2.1 Core spectrum monitoring network elements

The network architecture is considered in two levels. The first level is the interconnection of different devices within the spectrum monitoring station, which usually is performed via direct connection through a Local Area Network (LAN) or other point to point connections (USB, Fibre Optics).

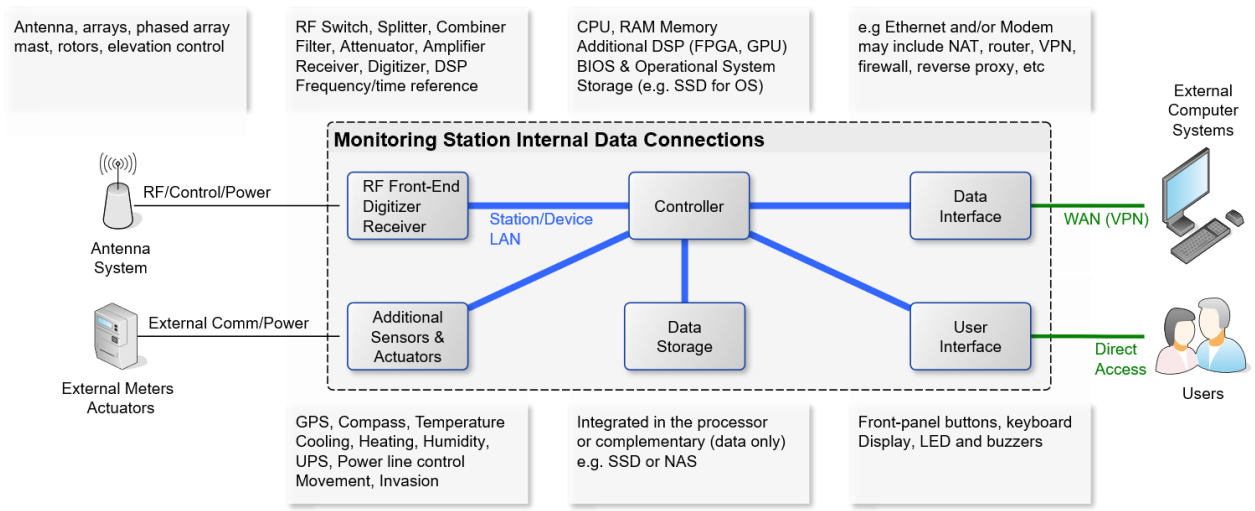
The second level is the Wide Area Network (WAN), which enables the networking of multiple fixed and/or mobile monitoring stations to perform tasks such as emitter location, propagation of AVD alarms, multi-site comparative measurements.

4.2.1.1 Connections within the monitoring station (LAN)

To better understand the data flow within a monitoring station, Fig. 4-3 presents a simplified model of a spectrum monitoring station with focus on the data communication between core components highlighted as: Receiver, Controller, Data Storage, Data Interface, User Interface and Additional Sensors and Actuators.

FIGURE 4-3

Simplified monitoring station diagram[1]



Parallels from this diagram to the detailed description presented in Chapter 3 can easily be made and the interested reader is encouraged to do so to better understand the functional characteristics of each element.

In this diagram, the connections from the core station equipment to antennas and other sensors are indicated in the left in light black lines, internal communication between core components are displayed in bold, blue lines and the external communication interfaces to users and other computer systems are displayed in the right side, in green lines.

Different systems might have different core components integrated and rely on external elements to provide additional functionalities, such as data storage, advanced data routing or even to act as the main controller. Solutions that integrate all core components into a single package that fits in the palm of a hand are available. Conversely, solutions are available that split each functionality into a different rack mount unit such that each component can be configured, used, replaced and upgraded independently.

[1] Icons from VRT Systems, 2014.

System operation is usually transparent when using TCP/IP protocols with commercial-off-the-shelf communication equipment such as switches, routers and modems. This also reduces the cost of deployment, operation, and maintenance. Other commercial products may be used as components for the monitoring station such as the controller, sensors, actuators, and data storage.

Some of these components may include an operation system (OS) such as MS Windows© or Linux©, to which access is desirable, most notably for maintenance purposes. There are technologies that allow seamless management across multiple operation systems and enforce a single OS. Although convenient for the users and maintenance personnel, this may impose undesirable restrictions on equipment selection and result in higher acquisition costs.

Regardless of the specific configuration of each system, the following sections will discuss how data management and automation are performed using this simplified model as reference for communication and automation within the data collection unit, in this case, a spectrum monitoring station.

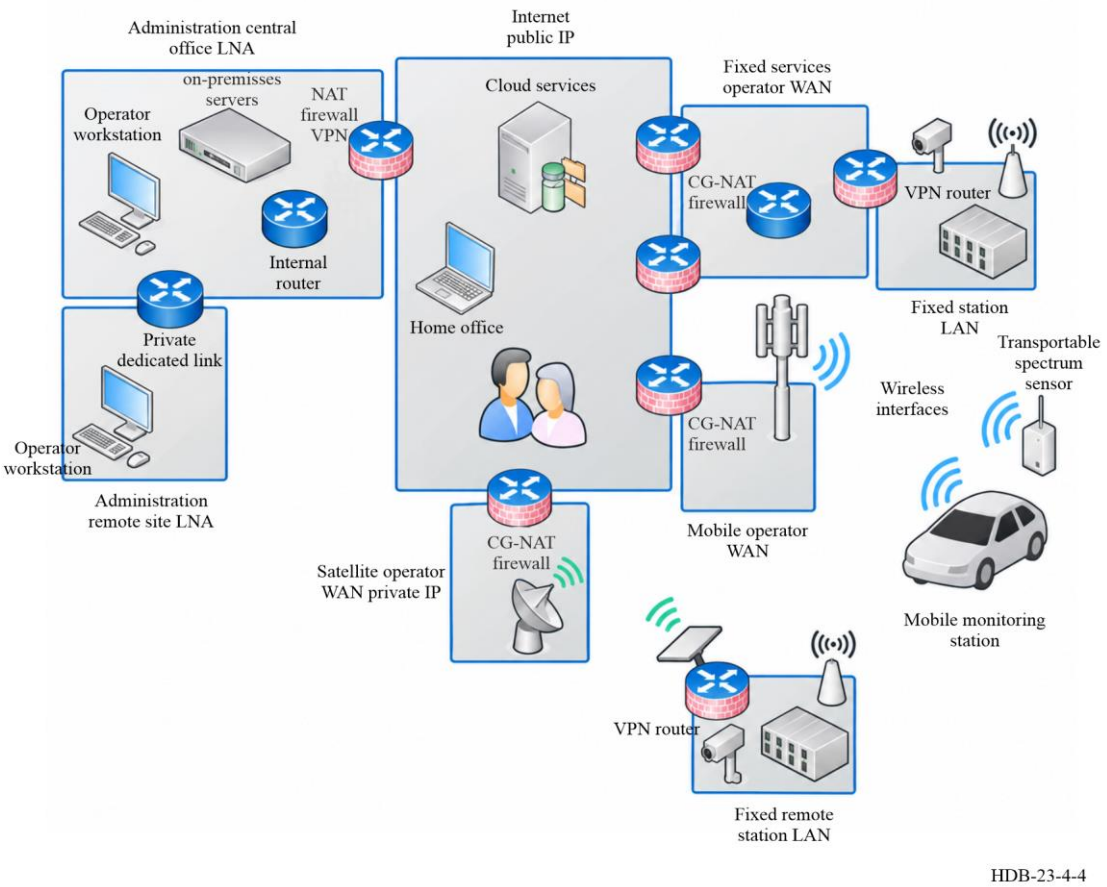
4.2.1.2 Connections between monitoring stations and control centres (WAN)

Wide area network (WAN) usually enables the data communication between monitoring stations and control centres. It is essential not only for real-time operation of remote stations and multi-station emitter location tasks, but also to various automated spectrum monitoring services: the upload of measurement scripts and reference data; the propagation of AVD alarms; the backup of measurement results and configurations to centralized servers; the monitoring of security alarms; and the maintenance of software components through patches and updates.

Figure 4-4 illustrates the interconnection between multiple spectrum monitoring stations and control centres.

FIGURE 4-4

Example for a spectrum monitoring network architecture[1]



As seen above, a large variety of different telecommunication networks may be used which enables flexibility of the system configuration. It may be established using wired or wireless connections, with almost any combination of terrestrial and satellite broadband telecommunication networks. The network configuration is usually more dependent on service availability at each location and the associated operating costs than any other aspect.

For fixed monitoring stations, terrestrial wired networks provide a reliable and stable connection for many different operations. In most cases, monitoring systems can be operated with data rates below 1 Mbit/s, which can be easily achieved by any service provider even using technologies such as xDSL, although the use of optical networks (PON) is preferable whenever available.

Wireless networks may be used to connect transportable and remote fixed monitoring stations installed in isolated areas where wired telecommunication links are not available. In such cases, private point-to-point radio links can be effectively used where there is a nearby endpoint with line of sight to the monitoring station. This can be accomplished using commercially available equipment that can provide data rates of several hundreds of Mbit/s at low costs.

Wireless networks are essential to connect mobile and transportable monitoring stations. The most common method of communications in these cases is the use of cellular networks maintained by telecommunication operators.

Although even IMT-2000 (3G) networks, in theory, provide data rates compatible with the requirements for monitoring station operation, the available upload rate from the monitoring station to the WAN, usually falls below acceptable conditions. Such networks may not be able to provide the operational conditions needed by spectrum monitoring services.

On the other hand, IMT-Advanced (4G) and IMT-2020 (5G) networks have been used with a variety of monitoring station models, providing reliable and stable operation, although conditions vary from site to site and with time of day, depending on the quality of service provided by the telecommunication operator and local use conditions. For instance, the use of mobile networks should be avoided for spectrum monitoring during major events when these networks may be saturated by the general public and result in quality of service that is not adequate to support the required spectrum monitoring activities.

If public wireless networks are unavailable and there is no easy alternative to install a dedicated point-to-point wireless link, one last alternative for remote sites is the use of satellite communications. This may be required even for stations installed near urban areas, for example, over a high hill with great line of sight to the urban area, but no local infrastructure and no coverage by mobile networks focused on lower ground.

Satellite systems can provide adequate data transmission over extremely wide areas, but use of Geostationary Satellites Orbit (GSO) will result in large delays (600 ms or more), degrading user experience for real-time operation, even to the point of compromising the use of some functionalities, depending on the specific vendor implementation, such as TDOA methods, especially when using mixed terrestrial and satellite networks. On the other hand, non-GSO satellite constellations, especially those operating in low-Earth orbit (LEO), can provide data connectivity with latency that may be lower than 100 msec, which will be less restrictive for monitoring system operation.

Radio telecommunication networks emitting in close proximity to a monitoring station may have adverse effects on its measurement quality, affecting antennas, receivers, DF systems and other equipment. Careful consideration should be given to the use of wireless technologies in support of monitoring services to ensure that they will not impact monitoring activities.

Some manufacturers provide integrated solutions that include wireless communication systems for communication using 4G and 5G mobile networks. Such out-of-the-box integration ensures that compatibility issues are properly addressed. Even if this option is not available or desirable due to local restrictions and conditions, interference problems may be averted by an attentive site installation which may employ directional antennas and independent communication modems, positioned to minimize the risk of interference between systems. Choosing a wireless technology that operates in frequency bands outside of the spectrum monitoring station operational range is an effective alternative to minimize such risks.

It is important to note that the introduction of higher latency/jitter and interference risks can limit remote operation, especially for time-critical functions, such as interference hunting. In such cases, local operation is preferred.

4.2.2 Spectrum monitoring network management

Modern spectrum monitoring networks may be understood as computer networks providing measurement services integrated into the spectrum management service along with other data and information services. As such, working methods, management solutions, and risks considered for computer networks may also be applied to maintain and secure the spectrum monitoring network.

To enable the use of standard network management technologies, individual components integrated into the spectrum monitoring network from different manufactures should follow well established interoperability standards. This should apply to all network levels from the physical layers of each device (network nodes) up to the communication protocols and data formats used, and from networked receivers to routers and power integrity management solutions.

The following subsections consider key aspects and tools to consider when planning and deploying a spectrum monitoring network.

4.2.2.1 Cyber security

Cyber-attacks pose a relevant risk of damage to spectrum monitoring equipment, compromise of data integrity and confidentiality, and interruption of system operation. Attacks may actively target individual station components, such as the controller, a router, or even a security camera. They may also passively monitor data being sent over a communications link to gather sensitive information, such as user and administrative passwords. Equipment within the monitoring station may also be used as means to attack other equipment inside and outside the administration network, thus posing additional institutional risks.

Securing a system after an attack can result in higher costs due to the time required to locate and repair the corrupted network component(s), with the added downtime of the service and its consequences.

The threat of attacks can be minimised by using standard computer security techniques appropriate to the risk. Examples are:

– Secure the direct access computer and network equipment interfaces, such as keyboards, screens, USB and network ports (physical security).

– Use secure communication links, either dedicated or though Virtual Private Network (VPN) when connecting multiple sites through public networks.

– Use strategies of Identity and Access Management (IAM, IdAM or IdM) such as passwords and multi-level privileges to control and restrict access by users to system functions and services through digital identities and associated access properties (software security).

– Use solutions for privileged access management (PAM) or secure password/key sharing to secure and manage service and maintenance access sessions and tokens.

– Employ the principle of minimal privilege (PoMP) or the principle of least authority (PoLA), to restrict the access to data and services only to identities (users and machines) that need it for a legitimate purpose.

– When off-the-shelf products are used, perform software/firmware updates and data backups of system components and configurations as recommended by the equipment and component manufacturers and the system integrator.

– Monitor network access and activities, looking for irregularities in the usage patterns of network, storage and processing resources.

– Regularly conduct security audits, checks and campaigns including penetration test and anti-phishing exercises to improve network security and user awareness to cyber-attack risks.

– Perform regular system training for operators and support personnel, including cyber security topics on the evolution of risks and industry regulations.

Many cyber security standards and practices have been developed and professional advice on the subject is recommended when deploying, operating, and maintaining a spectrum monitoring network. For isolated networks, air-gaps, physical hardening, and reducing the attack surface can be more effective than complex, maintenance-heavy frameworks. A key ITU-T reference on this subject is presented in Recommendation ITU-T X.1601 – Security framework for cloud computing.

4.2.2.2 Network observability

Traditional network monitoring focuses on collecting predefined metrics associated with the network nodes, including processing devices (e.g. processor, memory, storage), data links (e.g. upload and download rates, RSSI and other wireless network information), infrastructure (e.g. battery capacity, power quality and consumption), environment (e.g. location coordinates of the station, temperature, humidity) and security (e.g. rack door opening, movement, smoke detectors, cameras with image detection related triggers).

Additional service-related metrics may also be used, such as the availability of HTTP services provided by the monitoring station; logs from scheduled data collection tasks; Basic Instrument Self Test (BIST/BIT) periodic results, availability of TCP/UDP ports used for remote control and real-time operation; among others. Even measurement services may be evaluated, including for example the periodic measurement of known emitters to evaluate equipment operational conditions.

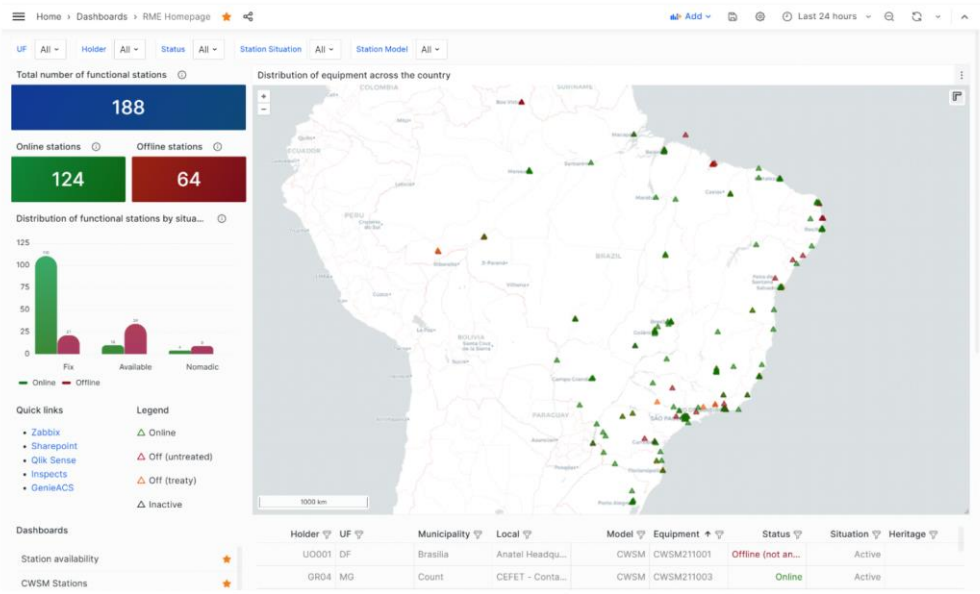
Network monitors use protocols like SNMP, TR69, flow records or syslogs to collect data. The monitored device (e.g. a spectrum monitoring station) may actively send information to a data collection service in the network, e.g. using SNMP Trap, HTTP request to ACS in TR69, or may passively wait for a query from the data collection service, e.g. using SNMP pool, a package using ICMP, or providing read access to log files in a network shared folder.

A combination of strategies is recommended to provide robust network infrastructure monitoring. Since spectrum monitoring stations may be loosely connected to the network core, the use of local agents and local data collection services may be a good strategy to avoid data loss due to temporary network failures that, in practice, have negligible impact on operations.

Network monitoring solutions usually include various means to define triggers based on known conditions to collect data, send messages to interested parties, and produce regular reports, including online data publishing through interactive dashboards as illustrated in Fig. 4-5.

FIGURE 4-5

Observability tool in a spectrum monitoring network



(a) Nationwide view of the spectrum monitoring network status

(b) Single station view of with operational parameters over a period of seven days

HDB-23-4-5

As the volume of telemetry data has increased and traditional dashboards and rule-based alerts struggle with scale, network monitoring has evolved into the concept of network observability, which proposes a holistic evaluation of rich telemetry collections. Although similar protocols and data collection methods are used, greater analytical capabilities have been added to help organizations and network management teams understand root causes and predict future issues by correlating multi-source data instead of evaluating individual network node parameters.

AI and ML are increasingly layered onto observability data, employing ML techniques such as clustering, anomaly detection, pattern mining to help surface issues. Such practices aim to reduce costs and enable proactive mitigation of network operational risks. In practice, ML can learn normal traffic patterns and detect deviations (e.g. a sudden flow from a dormant server), correlate multi-source metrics, and even predict failures. Many observability platforms now include AI features to auto-group related alerts or highlight unusual behaviour without human tuning.

Periodic logfiles/syslogs and simple threshold alerts has been traditionally considered sufficient for small deployments. while for large, highly networked environments, advanced observability, including features such as ML-based correlation, and OpenTelemetry are usually deployed. However, these advanced features are becoming more pervasive, enabling easier configuration and maintenance, thus being increasingly beneficial even for small use deployments.

4.2.2.3 Network configuration management

Network configuration management (NCM) tools provide the mechanisms to fully manage the networked infrastructure, such as to enable updates, install software patches, or to perform routine tasks such as centralized password management, conduct backup operations, perform hard reboot and system recovery.

Network configuration management may be essential for continuous operation of monitoring stations, especially those that may not be promptly accessible, such as when installed in distant locations or on towers or buildings with restricted access. It is also critical for the effective maintenance of the considerable number of devices that may comprise the spectrum monitoring network.

Tools used for network configuration are critical to enforce security policies within the network but also are a major risk factor, since they represent a channel though which network nodes may be accessed with high privilege profiles. As an example, some of protocols such as SNMPv0 and SNMPv2, commonly used in most appliances such as routers and UPS, are intrinsically vulnerable to cyber-attacks and require specific configuration and/or additional protection layers to be safely used.

4.2.3 General spectrum monitoring network architecture and cloud services

Different network architectures offer distinct trade-offs in terms of performance, scalability, resilience, and cost, and their adoption should reflect national priorities and regulatory requirements. Administrations should carefully consider not only the core network components, but also the entire process that determines how data is acquired, transferred, stored, and processed across monitoring stations, centralized facilities and cloud environments.

4.2.3.1 Local, centralized and distributed architectures

Local architectures rely on storage and processing resources integrated into each monitoring station. This approach maximizes independence and resilience against network outages but may limit scalability and make it more difficult to conduct system-wide coordination.

Centralized architectures concentrate storage and processing in a single national or regional facility. This simplifies management and facilitates integration with spectrum management databases but may create single points of failure and require high-capacity communication links.

Distributed architectures place storage and processing resources across multiple interconnected facilities, improving fault tolerance and scalability. When coupled with data-replication strategies, distributed architectures enable real-time data sharing and collaborative analysis across multiple monitoring sites, thus representing a good balance between centralized and local architectures.

4.2.3.2 Monitoring network data flow and the edge computing paradigm

The data flow within a spectrum monitoring network has traditionally been characterized by centralized communication, where measurement data from several fixed or mobile stations are transmitted to a control centre for storage, visualization, and analysis. While this architecture remains viable, the increasing complexity and data volume of modern monitoring operations, particularly those involving wideband receivers and continuous observations, has introduced new challenges related to bandwidth, latency, and interoperability.

Edge computing complements interoperability by redistributing intelligence across the network. Instead of transmitting raw data streams to the control centre, edge nodes perform local preprocessing, compression, and data validation, generating compact and meaningful datasets, such as occupancy levels, channelization results, and anomaly indicators, which are transmitted to the cloud or control centre for fusion and analysis. This significantly reduces bandwidth consumption and latency, while maintaining operational continuity through "first-in, first-out" (FIFO) based local storage cycles that ensure uninterrupted monitoring even during temporary network outages.

Distributed architectures combine automated data synchronization and distributed intelligence to transform the traditional network into a continuously updated and adaptive ecosystem, characterized by:

1) Optimized bandwidth usage and reduced latency. Local preprocessing and compression drastically decrease the amount of data transmitted while improving response time and reliability.

2) Interoperability across legacy and multi-vendor systems. Automated export of measurement results to monitored directories ensures that proprietary or legacy devices contribute seamlessly to the overall data flow, without requiring direct integration at the protocol level.

3) Operational continuity and resilience. Edge devices temporarily store processed data locally and automatically synchronize to the control centre once connectivity is restored, maintaining a more consistent and complete dataset.

4) Centralized intelligence and coordination. The control centre evolves from a data repository into an orchestration layer responsible for data fusion, high-level analytics, and policy-driven enforcement.

This edge-to-cloud data processing flow forms the foundation of next-generation monitoring systems, enabling administrations to transition from event-driven monitoring to continuous, proactive, and autonomous spectrum governance. It ensures that every stage of data processing not only feeds the next but also enriches the overall intelligence of the system, creating a feedback cycle that supports sustainable, data-centric regulation.

4.2.3.3 Cloud processing and serverless architectures

Administrations are now able to offload storage and processing to the cloud providing scalability and enabling monitoring systems to ingest and process large volumes of data. This can be accomplished without the commensurate front-end hardware investment. Cloud infrastructures can be deployed using container-based orchestration frameworks (e.g. Kubernetes, Docker Swarm), volume and object management solutions equivalent to those provided by companies as a shared resource. This results in a flexible deployment across hybrid local-cloud environments, ensuring consistent operation while scaling according to demand.

Several service models may also be applied to spectrum monitoring networks:

– IaaS (Infrastructure as a Service) provides virtualized computing resources, enabling administrations to replicate existing local or centralized infrastructures in the cloud, while managing low level aspects of the virtualized environment, such as which OS to use, how much memory and how many processing cores are allocated.

– PaaS (Platform as a Service) supplies a managed environment for deploying applications without maintaining underlying infrastructure, facilitating integration of monitoring software into cloud-native systems. PaaS delivers an environment to build/run applications, not ready-made applications.

– BaaS (Back-end as a Service) offers pre-built back-end services such as authentication, database management, and data storage, which can be leveraged for rapid deployment of spectrum monitoring portals and data-sharing platforms.

– FaaS (Function-as-a-Service, also known as Serverless architecture) enables computational functions to be executed on demand, without the need for the administration to maintain dedicated servers. This paradigm is particularly well-suited for event-driven spectrum monitoring tasks, such as anomaly detection, short-term data analysis, or automated reporting triggered by interference.

– SaaS (Software as a Service): A complete application delivered as a service. The user consumes the software via web interface, API, or client, without worrying about servers, OS, databases, or scaling. The application itself can be anything from direct spectrum monitoring interfaces and spectrum management systems to observability and complete VPN solutions for network host interconnection.

– Hybrid models combining these services are increasingly common. For example, administrations may use IaaS for bulk data storage, FaaS for automated quality control, and BaaS for exposing APIs to authorized stakeholders.

4.2.3.4 Considerations for adoption of cloud services in spectrum monitoring

When adopting cloud and serverless architectures, administrations should firstly consider data sovereignty and compliance with national regulations on storage location and cross-border data flows. There are open-source alternatives to deploy cloud-like services on premises enabling a progressive understanding of these technologies and facilitating a selective adoption of those services that can most benefit the goals of the administration. In any case, great care should be taken to ensure the ownership of the data, by considering security aspects including encryption, identity management and audit trails for data access.

Different architectures will result not only in distinctive characteristics in terms of reliability and available capabilities, but also in different acquisition and ownership costs. Usually, if the acquisition costs are lower, then the operational costs are higher. For example, long-term commitments to specific or proprietary solutions should be carefully evaluated and a superficial cost analysis of cloud services might be misleading.

A cloud service's life cycle may be adversely affected by vendor lock conditions and specific types of cyberattack [Dawood *et al.*, 2023] resulting in unforeseen costs. Cloud and serverless approaches incur recurring operational expenditure, carry vendor-lock risks, and require mature operational processes. On-premises/centralized deployments are the most common solutions and should be the default, particularly where data sovereignty is required.

4.3 Data collection

Understanding how data is collected and transferred across the elements of a spectrum monitoring network is essential as it affects every stage of the process from the procurement and deployment of new systems to the continuous operation of existing solutions and the future use of the collected data. Data collection is performed with equipment as described in Chapter 3, ranging from sophisticated receivers and fixed monitoring stations with complex antenna arrays to portable spectrum analysers and low-cost Software Defined Radio (SDR) devices, with specific capabilities or narrower operational scope.

Most monitoring systems include a User Interface (UI), through which equipment can be controlled, and measurement data visualized in real time. They often provide means of storing and sharing the data, enabling integration and post processing. However, not all devices offer standardized or open mechanisms for data storage, automation and external sharing. Such configurations may be acceptable when no further use of the data is intended, for example, handheld instruments used for local measurements may have limited benefits resulting from data sharing and automation. For many scenarios, manual measurements, local storage, manual file transfer and post-processing are sufficient and might be preferred, especially where security requirements are high or for complex measurements scenarios in which human and environment interactions are required.

Historically, many administrations deployed monitoring infrastructures composed of vendor-specific systems, each using proprietary interfaces and closed communication protocols. These configurations often resulted in vendor lock situations, where the exchange of data between systems was limited or required manual export operations, preventing full automation of the monitoring workflow. Consequently, valuable measurements were frequently stored in isolated environments, available only in restricted or text-based formats such as CSV or SM.1809-type files, which limited their usefulness for large-scale data analytics or real-time decision support.

The elimination of vendor lock does not result from edge computing itself, but from the adoption of automated data synchronization mechanisms that connect proprietary monitoring systems with open analytical platforms. In this approach, measurement results produced by vendor-specific equipment are automatically exported in standardized formats (e.g. CSV) to designated folders that are continuously monitored by a third-party or cloud-based system. The open platform then imports and processes these results automatically, incorporating them into the global information workflow without the need for human intervention. This simple but effective method allows existing proprietary systems to remain operational while becoming part of a continuous, automated, and interoperable data flow, avoiding dependence on closed architectures and enabling seamless integration into broader monitoring networks.

With the digitization of the spectrum management process and the associated documentation, it becomes increasingly challenging to integrate isolated or legacy systems into the modern, interconnected operational environments adopted by many administrations. It is not uncommon to encounter reports still based on photographs of a spectrum analyser display or similar low-quality formats that cannot be effectively integrated into the data lifecycle described earlier.

Building on this context, the following subsections present technologies and approaches that enable monitoring and measurement equipment to become elements of an integrated spectrum monitoring and management system and describe technical alternatives to this increasingly complex and relevant topic.

4.3.1 Spectrum monitoring data collection

Data collection in the spectrum monitoring network is performed using spectrum monitoring stations and receivers. Users may operate equipment directly and interactively, in real time, or through prescheduled and background tasks, gathering data for post processing.

Various levels of automation are available at most spectrum monitoring systems, including data reduction through parameter extraction, analysis and summarization. The local systems reduce the amount of data needed to be stored, generate real-time alarms, and perform a variety of similar tasks. Real-time processing of live or collected data is essential to most systems. For complementary information on the topic of automation and data integration within spectrum monitoring systems, refer to Recommendation ITU-R SM.1537.

An important example of data analysis and the summarization process is demodulation of detected emissions which may be critical to identify the source or qualify the intended use of the transmission. Processing of raw baseband I/Q data, including operations such as digital down-converter (DDC), digital filtering and software demodulation enable the production of text, audio, or video streams that may be compressed for better efficiency using specialized algorithms, thus avoiding the overload of data links and storage volumes. Advanced real-time features may also include continuous recording of raw data, which requires the use of temporary storage with dedicated data management policies to avoid burdening the other general system capabilities.

In any case, multi-level access control and prioritizing schemes are needed to avoid operational conflicts, since multiple operators and automated processes may simultaneously access the monitoring network measurement resources. In this complex scenario, auditing capabilities with continuous logging of operations are essential to trace user manual and automated activities to enable the identification of errors and cyber security threats for later corrective actions. Such auditing methods generate logs to be considered within the data lifecycle along with data produced by network observability, maintenance and management processes.

4.3.2 Manual data collection

For manual data collection, equipment may be operated from either an embedded front-panel interface or a software interface. The manufacturer usually provides the corresponding software package which may mimic the original front-panel or add features with a distinct set of capabilities. Having access to the basic functions is important since it provides a reference interface useful at least for calibration and testing.

Multi-vendor software solutions are an interesting alternative to reduce training costs since operators are then faced with only one familiar user interface to control different equipment efficiently. Multi-vendor alternatives may also be needed to integrate equipment from different manufacturers into existing measurement workflows and data management solutions.

For integration of the manual, real-time, data collection into the workflow, is essential that the UI allows the user to select and tag the required data and discard unnecessary information to efficiently manage and share the data.

4.3.3 Automated data collection process

To improve the ability to acquire monitoring data of interest, many spectrum monitoring systems include automation features. These features also have the benefit of improving the system efficiency.

The most basic automation feature is scheduling of the start and stop times of measurement tasks while reserving the necessary equipment resource. The next logical step would add the ability to create trigger events to control the workflow of the measurement script in a concept described as Event Driven Monitoring (EDM).

Trigger events may be generated by any system parameter, date and time from the system clock, platform location and speed from the Radio Navigation Satellite Service (RNSS); orientation using measurements from compass and accelerometers; and most notably, the detection of emissions or noise conditions as measured by the receivers. The Automatic Violation Detection (AVD) algorithm is a classic example of such event triggers based on RF measurements.

Once a trigger event is detected, the system may send alarms or change its monitoring task, for example, to start recording the demodulated information or I/Q data from the detected emission for a given period or until another event is generated such as the end of the transmission.

The definition of actions to be taken based on triggers correspond to a set of automation rules that consider expert-level operator knowledge concerning the task at hand. Such tasks are usually defined within the measurement scripts. Even complex tasks such as emitter location may be automated, for example, performing DF or TDOA measurements in a set of predefined channels. The results can be compared to the license database to increase the reliability of AVD alarms, enabling the detection of unauthorized use of licensed channels.

An important limitation of simple trigger-based automation is its inability to adjust the tasks in response to unpredicted events. Any optimization of the equipment resources based on the measurement results is limited to the trigger conditions configured by the knowledge and skill of the monitoring personnel who defined the measurement script.

Considering the use of monitoring systems with greater analytical capability, the measurement task may be defined with fewer inputs from the user, allowing the system to optimize the measurement parameters in response to the measurement results, following a concept that can described as a Dynamic Spectrum Monitoring (DSM). Various DSM algorithms may be employed according to the parameters to be optimized. As an example [Shi *et al.*, 2015], the system may change the revisit time of a given band based on the evaluated occupancy, ensuring the reliability of the results within a predefined confidence level for the occupancy measurement.

Further machine learning algorithms and strategies may be employed to improve the ability of the monitoring system to intercept emissions that are divergent from expected uses even with little initial knowledge of the spectrum at a given location. For example, the system may use clustering algorithms to group detected emissions and use a tagging interface to query the operators for further information that, over time, results in the identification of the emissions received at a given location, even with no available license database or frequency plan.

Section 4.6.3 discusses different modelling strategies that may be used to predict spectrum usage conditions and optimize the data collection process. Automated data collection processes may produce large volumes of data with implications throughout the data life cycle which should be considered when planning the monitoring network and its use.

Automated tasks related to the data workflow are also commonly available, including data synchronization between multiple sites and backup of essential configuration, logs, and system data.

Within this improved environment, edge computing complements interoperability by redistributing intelligence across the network. Instead of transmitting raw data streams to the control centre, edge nodes perform local preprocessing, compression, and validation, generating compact and meaningful datasets, such as occupancy levels, channelization results, and anomaly indicators, which are then transmitted to the cloud or control centre for fusion and analysis. This significantly reduces bandwidth consumption and latency, while maintaining operational continuity through FIFO-based local storage cycles that ensure uninterrupted monitoring even during temporary communication outages.

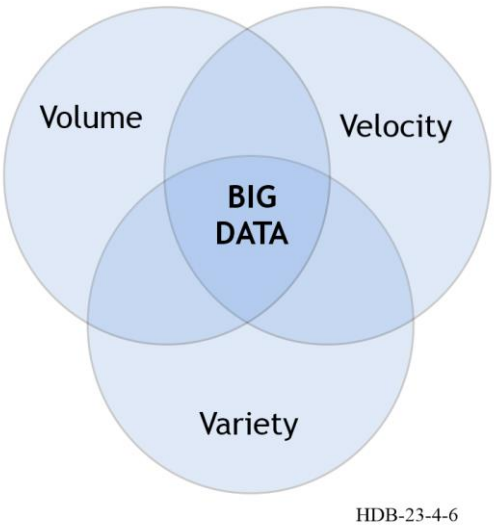
Finally, when considering the use of automatic systems, operators should be aware of the operational costs associated with the continuous operation of spectrum monitoring equipment. Such operation, in the long term, may degrade hardware elements faster (compared to standby modes) especially cooling systems and storage units, increasing costs for energy and maintenance. Thus, the use of background and automatic measurements should take into consideration the intended use, value, and cost of the collected data as well as the impact on the monitoring hardware. In short, data should not be collected that has no intended use or value.

4.4 Store, publish, archive, reuse and delete

Spectrum monitoring networks can produce large volumes of data in a brief period, up to gigabytes per second, including structured and unstructured data, thus usually falling into the 3Vs and the framework of big data management problems as defined by [Berisha *et al.*, 2022].

FIGURE 4-6

Big Data 3Vs



Monitoring stations may be configured to reduce the data throughput by strategies such avoiding the storage of I/Q data, maximizing trace bin size (FFT equivalent to RBW) according to each spectrum band requirement, or increasing revisit time according to the expected service behaviour pattern. However, spectrum monitoring equipment can generate large volumes of raw data, on the order of gigabytes per day, thus a large monitoring network may collect terabytes of data per year.

This section discusses the data lifecycle of spectrum monitoring data, formats and strategies to help administrations plan and manage the large volume of data to be produced.

4.4.1 Data formats

The definition and adoption of appropriate data formats is essential to ensure the reliability, interoperability, and long-term usability of spectrum monitoring information. Data formats determine how measurement results are structured, stored, exchanged and interpreted throughout the data lifecycle, from acquisition to archival to reuse. They should consider the technical characteristics of the measurement system, the expected data volumes and rates, and the need for compatibility with national and international data management frameworks.

Even though the data format internal to each specific data management and processing solution is irrelevant and most of the time inaccessible to the user, they become critical when considering the integration of different frameworks. For example, spectrum management and spectrum monitoring systems typically need to integrate data in a multi-vendor environment and share information between administrations.

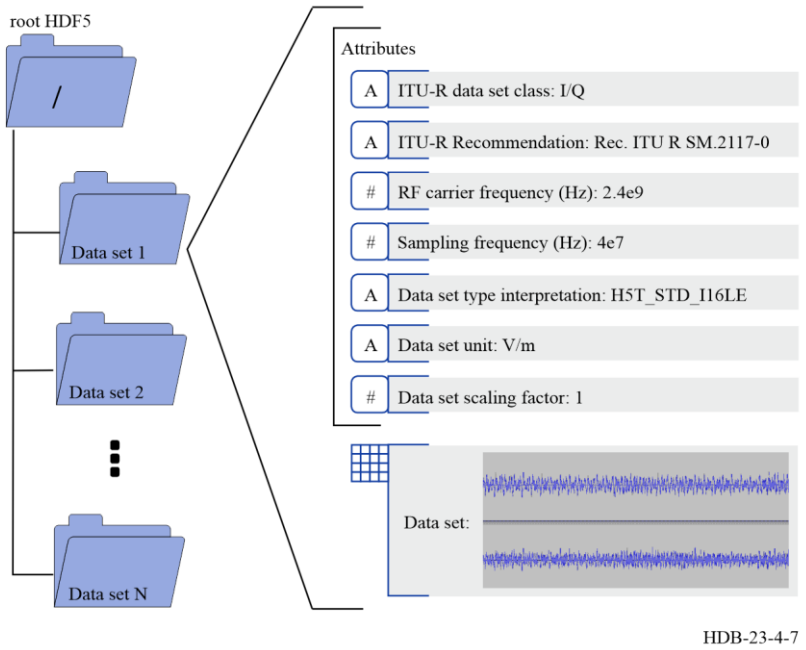
4.4.1.1 ITU standardized data formats

Large-scale, high-resolution measurements generated by spectrum monitoring equipment are most efficiently represented in binary data formats. These allow high throughput recording and compact storage while preserving the integrity of measured values.

Recommendation ITU-R SM.2117 defines a consistent binary structure for the exchange of raw in-phase/quadrature (I/Q) samples based on the Hierarchical Data Format, version 5 (HDF5) standard. HDF5 is an open standard that can represent any type of digital data in container-like structure as illustrated by Fig. 4-7 and may be used to store multiple data types into a single structured file. An HDF5 file may accommodate any type of data, from single numerical values to multidimensional tables. This enables a single file to also include information essential to describe the acquisition parameters, such as frequency limits, bandwidth, sampling rate, time reference, calibration data and equipment identification.

FIGURE 4-7

Example of container structure used in HDF5 with Rec. ITU-R SM.2117



HDF5 files are self-describing, using headers that describe each data value to enable independent decoding of the content by compatible systems.

For applications such as reporting, metadata exchange, and human-readable records, text-based formats may be appropriate. Recommendation ITU-R SM.1809 provides a common text structure for the exchange of monitoring data suitable for use in the spectrum management process including direct exchange between administrations.

Recommendation ITU-R SM.1393 describes a format more focused on standardizing human readable messages that, although outdated in some of its contents, is still relevant as a reference for standardized data communication. Such messages are intended for use as part of a "Memorandum of Understanding" to facilitate cooperation in spectrum monitoring matters between the administrations, as defined in Recommendation ITU-R SM.1394.

4.4.1.2 Open data formats

Beyond ITU defined formats, many solutions adopt open textual standards such as: CSV (Comma Separated Values, RFC 4180); DSV (Delimiter-separated values, where CSV commas may be replaced by semicolons, tabs and pipes.); JSON (JavaScript Object Notation, ISO/IEC 21778:2017); or XML (Extensible Markup Language, W3C XML 1.0 Recommendation) for interoperability between information systems. CSV and DSV formats are tabular data descriptions intended to store a single bi-dimensional table with rows and columns, while JSON and XML are able to store more complex data structures, from single values to multi-dimensional data tables and raw binary data.

These formats facilitate the publication and aggregation of monitoring data while maintaining adequate readability and transparency and are especially suitable for exchanging metadata between relational databases as described in Recommendation ITU-R SM.1370 which provides design guidelines for developing automated spectrum management systems and Recommendation ITU-R SM.1537 that recommends administrations consider using integrated systems with a common relational database for spectrum monitoring and automated spectrum management.

When spectrum monitoring data is associated with geographical data, more specialized text data formats such as KML (Keyhole Markup Language, OGC KML 2.3), it is zip compressed variant KMZ, and other geospatial file formats such as GML (Geography Markup Language) and GeoJSON are common.

Although used throughout the industry, textual formats are not suitable for large datasets and limit the efficiency of data integration for systems operating in the context of Big Data, in which case, the use of binary formatted data is recommended.

Apart from the HDF5, other open data formats may include hierarchical organization, internal compression, and efficient access to subsets of the data. The most notable examples are Apache Parquet and ORC (Optimized Row Columnar). A key difference between these formats is that while HDF5 is a container based hierarchical format, enabling the storage of multiple tables and data values within a single file, like what is found in JSON and XML files, Parque and ORC are tabular like CSV, but with the benefits of digital formats. These last two formats outperform HDF5 in many use cases, but their singular table-like structure may limit their application when representing complex datasets.

SigMF is specifically tailored for radio applications created by the GNU Radio community to store and exchange recorded RF signal data for offline processing and analysis. It defines a simple and extensible structure consisting of raw signal datasets (typically I/Q samples but may include data array information, such as temperature or location) accompanied by human- and machine-readable metadata serialized in a JSON format. SigMF defines a core namespace to be used for the metadata content, which may be extended for specific applications.

An example of the use of SigMF in spectrum monitoring can be found in the work of the IEEE 802.15.22.3 Task Group, formed to standardize a Spectrum Characterization and Occupancy Sensing (SCOS) system [Zhang *et al.*, 2019]. The use of ITU standards and Open data formats enhances scalability, supports multi-platform processing environments, and promotes interoperability between different analytical tools and software frameworks to ensure data accessibility without dependence on proprietary applications.

4.4.1.3 Proprietary and other data formats

Many commercially available spectrum monitoring solutions employ their own proprietary data formats, either as a BLOB (Binary Large Object) within a relational database, or as individual binary files stored on the monitoring station and indexed with a set of metadata within a data management system (e.g. SQL, NoSQL, Object Storage). Such formats usually are variants of those used for data streaming between the receiver digitizer and the processor responsible for data storage, thus reducing the complexity of real-time data processing, since the data is stored with only minor changes from the original raw data delivered by the receiver. This maximizes the data throughput to a permanent local storage (e.g. hard disks). Some manufacturers provide specifications of the binary format used by their systems and even publish libraries on open-source repositories that can be used to access the data directly, enabling easier integration of the data into a broader data management solution.

Access to the recorded spectrum monitoring data may also be provided in the format of an API or DLL that can be used to convert data from the proprietary format into one that can be efficiently used by other analytical tools and data management solutions. This is not the most desirable scenario. Since a pre-compiled DLL will be restricted to a specific OS version and architecture, it might be rendered useless if the underlying infrastructure cannot be provided or maintained due to obsolescence or cybersecurity issues. For example, it might be extremely hard to integrate a DLL that was made to run only on a 32-bit OS from ten years ago. Even if the executable can be run on a modern OS, it will require additional software components to allow the communication between the 32-bit architecture and a more current 64-bit architecture.

In any case, the programmatic access to the recorded data is essential for the implementation of most data management solutions and may require specific software licenses and conditions. This should always be considered when procuring new equipment and spectrum monitoring solutions, keeping in mind that good RF receivers might have a longer operating lifetime than the associated commodity equipment such as computers.

4.4.2 Data transfer and storage

The ability to transfer and store spectrum monitoring data is critical to the overall operation of any data-management framework. This ensures that measurement results are reliably preserved for long-term use and determines how quickly and effectively the information can be accessed, processed and shared between stations, operators, management systems and databases.

Storage solutions should therefore balance performance, cost, security, and scalability while ensuring compliance with national regulations while also observing international recommendations. Local storage is standard for most applications while centralized/cloud storage is optional. Many workflows do not need a central data lake and could be even hindered by it.

4.4.2.1 Local and remote storage

Most spectrum monitoring solutions rely on local storage integrated with the station (e.g. hard-disks or solid-state drives) to maintain the data required for its operation and to store measurement and monitoring results. Local storage provides full control over the hardware and software environment, operation without continuous internet connectivity, and ease of compliance with strict data-sovereignty requirements. However, it is constrained by hardware capacity, maintenance costs, and the effort required to ensure redundancy and disaster recovery.

Some modern systems adopt remote storage solutions, streaming the collected measurement data directly to clients or a centralized server responsible for the data management. Remote storage provides virtually unlimited scalability, elastic allocation of resources, built-in redundancy, and geographic distribution, with monitoring data stored closer to analytical resources or end-users. However, such solution is prone to critical failures due to problems in the communication links, thus increasing the operational costs associated with implementing more stable and reliable communication between monitoring stations and the centralized services.

Hybrid approaches, where raw or time-critical data is stored locally while aggregated or historical data are migrated to the centralized services, are also becoming common, particularly when integrating monitoring systems with national or regional data lakes and regulatory databases.

Centralized servers may also be a source of problems creating a Single Point of Failure (SPOF) that may result in system-wide outages. To avoid such scenarios, consider using redundant centralized server architectures that include cloud services for communication, storage and processing.

When deciding between local or centralized private storage and the use of cloud services, administrations should consider:

– Data sovereignty and regulatory frameworks (laws governing the location of data storage and cross-border transfers).
– Latency and bandwidth requirements, particularly when real-time or near-real-time access is needed.
– Security considerations, including encryption, access control, and auditability.
– Cost models, as cloud services typically operate on subscription or pay-per-use models, while local storage requires upfront capital expenditure and ongoing maintenance.

4.4.2.2 Storage levels and data availability

To enable a cost-effective handling of large volumes of data, such as that produced by spectrum monitoring systems, various storage architectures can be used. These are often described as hot, warm, and cold data storage:

– Hot storage refers to fast-access storage for recently acquired or frequently accessed data. It is typically implemented with SSD arrays or high-performance cloud storage tiers. Hot storage is essential for real-time data collection and operational dashboards.

– Warm storage provides medium-speed access at reduced cost, suitable for data that are not continuously required but should remain readily available for analysis, regulatory investigations, or mid-term studies. This tier often uses high-capacity HDD arrays, object storage or moderately priced cloud tiers.

– Cold storage is used for long-term archival of rarely accessed data. It emphasizes cost efficiency and durability over speed, and is often based on tape libraries, optical media, or deep-archive cloud services. Cold storage is essential for compliance with retention policies, legal evidence preservation, and long-term research datasets. An example of cold storage might include a detailed historical review of spectrum measurements showing the evolution of spectrum usage in a specific area.

An effective storage strategy defines clear policies for data lifecycle management, including retention periods, migration between tiers and deletion procedures while maintaining integrity and traceability across all storage levels.

4.4.2.3 Data integration and architectures

Spectrum-monitoring systems and services generate heterogeneous data, ranging from raw I/Q samples, processed spectral traces, metadata and reports. The efficient integration of these datasets requires well-defined storage and processing architectures, compatible with the administration's requirements in terms of workflow and volume of data to be processed.

Traditional spectrum management systems usually rely on Relational Databases (SQL) for structured data such as licenses and frequency assignments. Binary large objects (BLOBs) containing actual measurement data may also be stored in SQL databases, although this approach is often inefficient and not recommended.

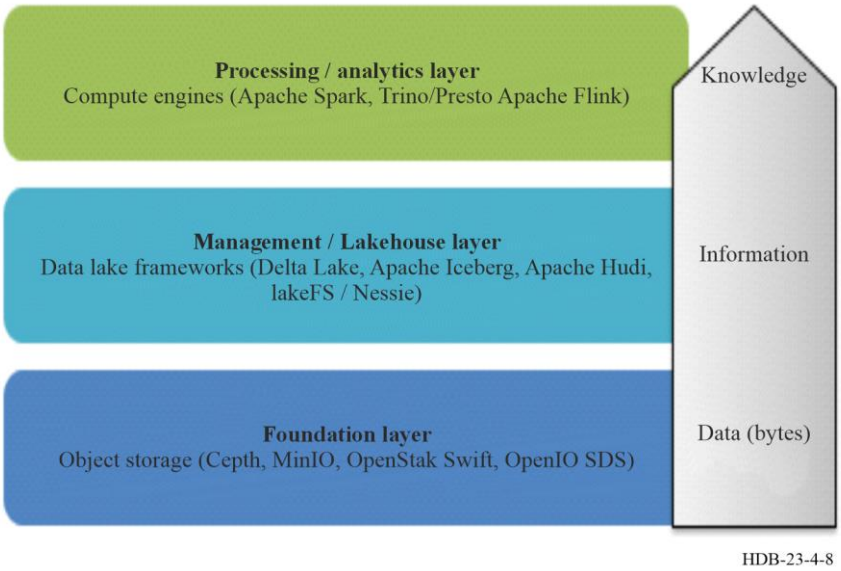
Non-relational databases (NoSQL) such as MongoDB and Cassandra may also be used to store non-structured documents such as reports, documents and text data in general, which may be too variable in nature to enable the efficient use of a relational database. These types of database management systems are also inefficient when considering binary data produced by spectrum monitoring stations. Raw monitoring data and other high dimensional representations of spectrum monitoring data mostly maintained as isolated files, sometimes linked to a local database through a set of metadata used to provide easy access for analytical tools.

Scaling up this simple model of file and metadata storage introduces the major frameworks used for Big Data, which include: a foundation layer (e.g. Object Storage); a data management layer (e.g. data lake frameworks); and a processing and analytical layer where Compute Engines can process the data and answer end user requests.

There are numerous solutions that may be adopted. Figure 4-8 shows examples of major open-source alternatives available for each of these layers.

FIGURE 4-8

Object Storage, data lake and analytical engine solutions



When considering integrated data storage and management architectures, key aspects to consider are:

– National/Local conditions, such as IT policies and regulations, available expertise and cost structures.
– Support for both legacy SQL-based systems and modern approaches.
– Interoperability with Open and ITU-standardized formats.
– Use of APIs and middleware to abstract hardware or vendor specific implementations.
– Clear data-governance policies defining ownership, access rights, and retention schedules.
– Risks associated with the proposed architecture, especially considering the possibility of unwanted future restrictions on the adoption of innovative technologies.

4.4.3 Data management

Effective data management ensures that spectrum monitoring information is handled consistently, securely and in ways that maximize its long-term value. This is vital to maintain acceptable operational costs, enabling administrations to derive the maximum benefit from their investments in spectrum monitoring infrastructures. Data management encompasses policies for data sharing and protection, mechanisms for organizing and cataloguing information, methods for publishing and exchanging datasets, and strategies for discarding data that no longer serves operational or regulatory purposes.

4.4.3.1 Data policies and governance

Data management is established by clear policies regarding ownership, access rights, retention periods, and conditions for sharing data with third parties. Concerning data sharing, a key aspect to consider is the value of open data policy. Making non-confidential monitoring results publicly available can promote transparency, enable independent research, and support the development of new services. Open-data principles should be applied to maximize accessibility while safeguarding security and privacy; and should only be used where legally and operationally appropriate, while confidentiality and data protection take precedence. Particular attention should be given to personal data protection in accordance with national legislation. Any data that may even indirectly identify individuals (e.g. location or usage patterns) should be handled responsibly. In this context, the adoption of the FAIR principles (Findable, Accessible, Interoperable, Reusable) (Wilkinson *et al.*, 2016) provides administrations with a practical framework for aligning technical data-management practices with policy objectives. Data policies define ownership, retention and access rights, while governance mechanisms ensure compliance through oversight and accountability.

By requiring that monitoring datasets and their metadata be managed according to FAIR, administrations can translate high-level policy goals (such as transparency, interoperability, and long-term reusability) into operational requirements that maximize the value of spectrum monitoring information. The FAIR principles were first introduced in 2016 and have since been widely adopted by international organizations, including the European Commission Expert Group CODATA and the GO FAIR Initiative.

4.4.3.2 Metadata, standards and interoperability

Maintaining spectrum monitoring datasets requires a comprehensive definition of the metadata to be used. Although most off-the-shelf solutions include essential metadata as a starting point, usually such definitions are configurable and can be extended to encompass an administration's specific requirements. It is, therefore, essential that a clear view of the needed metadata is established in accordance with the governance policy.

Essential metadata is expected to clearly describe the measurement context to enable traceability and accurately summarize the context of the associated measurement results, including:

– Identity of the equipment and operator responsible when manual activities are performed, including equipment setup and antenna positioning. (who[2]).

– The adopted measurement procedure including system configuration. This can also be extended to include aspects such as the work person-hour required to enable operational cost estimation. (how, how-much[2]).

– Identity of the object of measurement, e.g. location, frequency band, start/stop times, and, whenever applicable, emitter identification. (what, where, when[2]),

– Identity of the party requesting the measurement, e.g. a regular spectrum monitoring plan, an interference complaint. (why[2]).

– Data management and policy related information, e.g. stakeholders (considering any restriction levels), associated access groups or individuals (who/ to whom[2]), applicable maintenance and discard policies (how-much / when[2]).

Metadata can be enriched by advanced descriptors generated by analytical processing of results, from classical parametric measurements such the estimation of centre frequency and occupied bandwidth of an emission, to more advanced parameters, such as vectorial and model-based representations of the results or descriptions derived from large language models (LLMs) or other machine-learning techniques. Such descriptors may be useful to enhance searchability and might be relevant to enable pattern recognition methods.

Going beyond the simple metadata scope definition by adopting internationally harmonized metadata models and ontologies, administrations can ensure that spectrum-monitoring datasets can reliably be exchanged between heterogeneous systems, integrated with other national and international databases, and preserved for long-term reusability.

Multiple efforts are underway by organizations such as: the World Wide Web Consortium, with the development of standards for RDF (Resource Description Framework) and OWL (Web Ontology Language); the Open Geospatial Consortium (OGC) with more specific extensions for the geospatial segment; the Dublin Core Metadata Initiative (DCMI) with general-purpose set of metadata elements for descriptive and archival purposes; and the BIPM Digital Transformation Initiative, which is leading work on standardized metadata frameworks for metrology, providing machine-actionable data structures and ontologies that can also serve as a model for representing SI physical quantities in the context of spectrum monitoring measurements.

To ensure long-term consistency, all adopted data formats should include explicit version identifiers, schema documentation, and validation mechanisms. Whenever required, the integration with proprietary or legacy formats can be performed through conversion utilities or gateway services that can export information into open formats for archiving and exchange.

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[2] Pronouns indicated in parentheses within this item list are in reference to the 5W2H problem solving method, commonly used in business, project and quality management. The numbers and letters refer to the use of the pronouns: What, Who, Where, When, Why, How, How much.

4.4.3.3 Data catalogue and archive

Traditionally, monitoring solutions relied on simple directory structures and file naming conventions to provide users access to the desired data, and although this is still viable when considering very small teams with limited equipment, it is very hard to maintain. Integration of this type of data organization into a modern spectrum management environment would be extremely difficult.

To ensure that datasets remain discoverable and usable over time, the metadata associated with spectrum monitoring activities can be organized into a data catalogue, a structured inventory, and describe the datasets collected, the content, coverage and access conditions. Data catalogues facilitate internal operations, enable efficient queries, and support cooperation between administrations by providing clear descriptions of available information. Data catalogues ensure the traceability of data across multiple storage types such as hot, warm and cold storage tiers (described in § 4.4.2.2), enable the archive process to be conducted in a seamless process, and ensure long-term preservation, integrity and traceability of monitoring datasets. It also supports data reprocessing using more advanced analytical methods.

4.4.3.4 Data discard strategies

Given the continuous and high-volume nature of spectrum monitoring activities, it is neither practical nor desirable to retain all data indefinitely. Therefore, clear data discard strategies should be adopted which may include:

– Relevance-based discard, where data are deleted once they are no longer needed for operational, regulatory or research purposes. For example, I/Q data can be discarded after analysis and summarization if no need for reprocessing is conceivable.

– Time-based discard, where data are automatically removed after a defined retention period unless it has been specifically flagged for preservation.

– Model-based discard, where data selection is guided by analytical methods, retaining only statistically or operationally significant subsets. For example, in the case of mobile/transportable stations, retaining at least one measurement set descriptive of the spectrum usage for each location, and for fixed stations, maintaining such measurements for five years for historical purposes.

Discard policies should ensure that essential information required for regulatory or legal purposes is properly maintained, and that archived datasets remain representative and usable for long-term analysis.

4.5 Process and analysis

To achieve effective automation under complex and dynamic spectrum environments, a robust processing framework capable of handling high volume RF data is essential. While AI has demonstrated success across diverse fields, empirical evidence does not yet confirm that Deep Learning (DL) is the optimal solution for spectrum monitoring. Furthermore, DL is unlikely to supersede rigorous theory-based measurement and analytical computations. Accordingly, the well-established techniques detailed in this handbook should be viewed as complementary to data-driven inference, rather than as a replacement. An important review of different machine learning usage in communication systems can be found in the work of [Respati and Lee, 2024], which further expands this discussion.

To present traditional spectrum monitoring techniques and data-driven intelligent analysis within a unified framework, the monitoring process is structured as a continuous workflow divided into distinct operational phases. This modular approach facilitates a holistic understanding of how emerging learning-based technologies align with established measurement methodologies.

The automated spectrum monitoring process can consist of two primary phases that commence after the analogue to digital conversion:

– Signal Conditioning and Structuring. This phase focuses on the derivation of salient features through domain-expert intervention, transforming high-dimensional raw waveform data into structured, discriminative representations suitable for automated processing.

– Intelligent Analysis and Inference. Building upon the structured data, this phase employs advanced algorithms to perform autonomous signal classification, identification, and operational intent assessment.

By categorizing these processes into elemental techniques, this section establishes a standardized foundation for automation, prioritizing generalized methods that have achieved sufficient technical maturity.

4.5.1 Signal conditioning and structuring

The first phase, Signal Conditioning and Structuring, is the foundational process in which raw RF data are converted into a format suitable for reliable analysis and interpretation. It comprises four key sub-processes – (1) Signal Conditioning (or Pre-processing), (2) Signal Formatting, (3) Signal Detection and Segmentation, and (4) Feature Extraction – which together constitute the core of this phase in automated radio-monitoring systems. During this stage, raw data are systematically transformed into actionable information. The resulting structured data are then transferred to the Intelligent Analysis and Inference phase, where specific monitoring objectives are ultimately achieved. These objectives may include illegal-signal detection, interference-source identification and frequency-usage analysis.

4.5.1.1 Signal conditioning (or pre-processing)

Signal conditioning, also referred to as pre-processing, is the first refinement applied to raw RF data captured by sensors. Although the digitized RF data has already undergone analogue front-end processing (e.g. filtering, receiver gain control), a proper level of conditioning at the digital stage is required to perform specific signal-processing. The primary objectives are twofold: (1) to remove or minimize the impact of undesirable components such as noise, interference and distortion, and (2) to stabilize the intrinsic characteristics of the received signal.

This stage is indispensable because raw data are highly susceptible to contamination from environmental factors and intrinsic system noise. If left unmitigated, this can severely degrade the accuracy of downstream analytics, leading to false detections, misclassifications, and unreliable conclusions. Hence, signal conditioning establishes the foundation for trustworthy analysis by maximizing the quality of the acquired data.

Typical refinements include:

– Filtering: Passes or blocks designated frequency bands to attenuate noise, interference, or spurious emissions – for example, digital band-pass and notch filters.

– Automatic Gain Control (AGC): Automatically regulates output-signal amplitude, keeping it constant despite fluctuations in received-signal strength – critical for signals with large dynamic range.

– DC Offset Removal: Eliminates unwanted DC components introduced by receiver imperfections, thereby restoring a correct signal baseline.

– Time/Phase Synchronization: Aligns time and phase across multiple channels or sensors, enabling precise temporal correlation of collected signals.

Well-designed signal conditioning delivers several benefits: an improved signal-to-noise ratio (SNR), stabilised signal characteristics, reduced distortion, enhanced performance of subsequent feature-extraction and analysis algorithms and a significant increase in analytical reliability.

4.5.1.2 Signal formatting

Signal formatting is the process of converting conditioned signal data into a structured, standardised form so that it meets the input requirements of downstream analysis algorithms. Because sensors and acquisition systems generate data in highly variable formats – and because subsequent tasks such as feature extraction, classification, and identification often demand specific representations (e.g. time-domain waveforms, frequency spectra, or time–frequency maps) – this step is essential for interoperability and processing efficiency.

Typical conversions include:

– I/Q-Data Conversion: Transforming raw in-phase/quadrature samples into alternative representations, such as amplitude/phase or power-spectral density (PSD), when those formats are more suitable for a given analysis.

– Resampling: Adjusting the sampling rate to a common standard or to the rate required by subsequent processing stages.

– Framing: Dividing continuous data streams into fixed-length frames (time or frequency domain) so that each segment can be analysed independently.

– Metadata augmentation: Appending contextual information – timestamps, frequency-band descriptors, sensor IDs, geolocation tags – to support efficient data management and richer analytics.

– Time-frequency transformation: Applying tools such as the Fast Fourier Transform (FFT) to convert time-domain data into frequency-domain or time–frequency representations (e.g. spectrograms).

Effective signal formatting delivers several benefits. It guarantees interoperability across diverse systems and algorithms, enforces consistent input formats for analysis workflows, simplifies data management and storage, and accelerates downstream processing.

4.5.1.3 Signal detection and segmentation

Signal detection and segmentation form a pivotal stage in automated radio-monitoring workflows. This stage comprises two tightly coupled tasks:

– Detection: Identifying the presence of signals within the RF data stream; and

– Segmentation: Isolating the specific portion(s) of the stream that contain the detected signals.

Together, these operations distinguish genuine signal events from ubiquitous background noise or other unwanted emissions.

Because radio-monitoring systems capture data continuously while the events of interest may occur only intermittently, analysing the entire stream is computationally inefficient. By confining subsequent processing to segments most likely to contain signals, detection and segmentation focus analytical resources where they are most valuable, reduce computational load, and accelerate overall system throughput. Moreover, isolating individual signal events is indispensable for any detailed, signal-specific analysis.

Methodologies for signal detection were developed under the concept of spectrum sensing [Moessner *et al.*, 2013; Perera & Herath, 2011] which basically groups portions of the spectrum into two categories: signals of interest, and background noise. Some methods require little knowledge about the data itself (blind sensing) such as Covariance Analysis, ITC or Wavelet. Other methods require more information about the differences between noise and emission characteristics either from expert configuration based on a priori knowledge or an ML training process.

Energy-based detection methods may vary from simple fixed thresholds to more sophisticated approaches, such as GFT and Bayesian Detectors [Adams & MacKay, 2007] or employ trained neural networks and deep learning [Chan *et al.*, 2019; Fehske *et al.*, 2005; Selim *et al.*, 2018].

Where the emission characteristics are better known, methods such as matched-filter coherent detection, second order cyclo-stationarity, and autocorrelation may be applied. (non-blind sensing).

A mixed method, applying several of the above alternatives to evaluate a spectrum band in successive stages may provide a better result, including the use of more advanced ML techniques to select the appropriate method according to the results obtained in the initial stages of the analysis.

Once portions of the spectrum data stream are identified, they may be segmented into smaller datasets for further processing. Such segmentation may be based on the same criteria used for detection. For example, once a signal is detected, it should be extracted from the noise background as a separate data stream, e.g. Threshold-Based Segmentation.

Segmentation may also be conducted based on other criteria, such as: Fixed-Length Segmentation, e.g. splitting data into segments of a predetermined, fixed duration starting from the point of detection, or Model-Based Segmentation, where signal properties, such as modulation patterns or other characteristics are evaluated to identify and segment the precise start and end points of the signal event. Practical examples include burst-signal segmentation in HF surveillance (preparing inputs for modulation recognition) and spectrogram generation for deep-learning classifiers.

Successful implementation of the detection and segmentation stage substantially reduces the data volume passed on to computationally intensive post-processing. It also enables near-real-time operation and markedly improves the probability of detecting intermittent or transient signals.

4.5.1.4 Feature extraction

Feature extraction is the process of deriving salient information from segmented signal portions. The resulting features – such as centre frequency, occupied bandwidth, in-band power distribution, transmission length, inter-burst spacing, modulation type, modulation-specific parameters and AOA or TDOA location estimation – capture the distinctive characteristics of each signal.

In traditional spectrum monitoring workflows, feature extraction is often inseparable from the inference task itself. By contrast, in ML and DL approaches, it is treated as a domain-expert step responsible for generating structured inputs for automated algorithms.

Because raw waveforms are high-dimensional and highly variable, applying ML or DL directly to them is computationally burdensome and often impractical. Feature extraction addresses this constraint by yielding compressed, discriminative representations that both reduce dimensionality and enhance subsequent analytical accuracy. Carefully selected features enable reliable determinations of signal type, origin and operational intent.

This process produces several types of features, which include but are not limited to:

– *Time-Domain Features*: Derived directly from the signal waveform data in the time domain; such features include maximum and minimum amplitude, root mean square (RMS) value, transmission length, and zero-crossing rate.

– *Frequency-Domain Features*: Based on the frequency representation of the signal, these features include bandwidth, centre frequency, power spectral density (PSD), spectral shape descriptors, and flatness.

– *Modulation Features*: Designed to capture modulation-specific characteristics, this category includes higher-order cumulants or moments, analysis results derived from constellation diagrams, and cyclo-stationary features such as α–β plane representations.

– *Time-Frequency Features*: These capture joint information in both time and frequency domains, and include features derived from spectrogram images and wavelet coefficients.

When implemented effectively, feature extraction provides several critical benefits, including:

– Significant reduction in data dimensionality

– Enhanced discrimination between different signal types

– Optimized performance of classification and identification algorithms

– Increased speed and efficiency in signal analysis

– Automated signal recognition and decision support.

The successful implementation of feature extraction brings multiple critical advantages to spectrum monitoring workflows. It serves as a foundational enabler for automated and intelligent signal analysis systems by reducing raw data complexity and volume while preserving key discriminative attributes.

4.5.2 Intelligent analysis and inference

While Chapter 5 of this Handbook concentrates on conventional theory-based signal-processing techniques and non-deep ML methods, the present chapter will focus on the data centric approach, considering AI-based analysis.

Table 4-2 organizes some of the main Learning Paradigms and Model/Architectures. Learning paradigms can be categorized according to how intelligence is learned from data into supervised, unsupervised, and reinforcement learning; more finely, self-supervised (labels created from data) and semi-supervised (few labels + many unlabelled) approaches can also be distinguished. Model/Architecture refers to the model being trained; in DL approaches, the model assumes a multi-layer neural-network structure and, through training, acquires the specific parameter value weights required at each stage.

TABLE 4-2

Learning paradigms and Model/Architecture of ML

Learning paradigms	**Model / Architecture Families (ML)**	
	ML (Non-Deep)	**ML (Deep/DL)**
Supervised (labels provided)	SVM (Support Vector Machine), Random Forest	CNN (Convolutional Neural Network), RNN (Recurrent Neural Network), Transformer, LSTM (Long Short-Term Memory), NLP (Natural Language Processing)
Unsupervised (no labels)	K-Means, PCA (Principal Component Analysis), GMM (Gaussian Mixture Model)	Autoencoder-series, Deep clustering
Reinforcement Learning (RL) (reward-driven interaction)	Q-learning	Deep RL

The following sections describe these models and the principal learning paradigms in greater detail.

4.5.2.1 Machine learning and deep learning

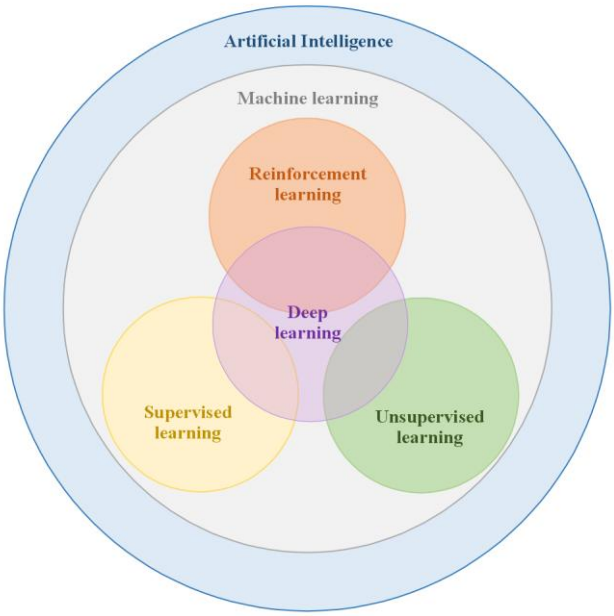
At the heart of intelligent analysis in automated radio-monitoring systems are the powerful paradigms of Machine Learning (ML) and Deep Learning (DL). ML is a broad field within Artificial Intelligence that enables systems to learn from data and to make predictions or decisions without explicit rule-based programming for every scenario. DL is a major sub-field of ML that employs multilayered artificial-neural-network architectures – hence the descriptor deep.

Although ML and DL share the overarching goal of learning patterns from data to support inference, they differ in their treatment of features. Traditional ML methods usually require domain experts to hand-craft relevant features from raw data, whereas DL models can automatically learn hierarchical representations and complex features directly from raw or minimally processed inputs. This capability makes DL particularly effective for tasks that involve large volumes of high-dimensional data – such as spectrogram images or intricate RF time-series data.

The adoption of both ML and DL in modern radio monitoring is essential because today's RF environments generate data of unprecedented volume, velocity, and variety, overwhelming traditional analytical techniques. ML and DL can automatically discern subtle patterns, classify a wide range of signal types, detect anomalies that may indicate unusual activity, and draw reliable inferences in a dynamic spectrum. Their capacity to learn from extensive datasets is crucial for adapting to the evolving signal characteristics and complex interference scenarios encountered in real-world deployments.

FIGURE 4-9

Key AI concept relations



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During the Intelligent Analysis and Inference phase, both Machine-Learning and Deep-Learning paradigms contribute a range of practical techniques:

Machine learning examples in radio monitoring

– Support Vector Machines (SVM) – classify signals using domain-expert feature.

– Random Forests – identify and characterise interference sources.

– K-Means Clustering – group unauthorised or unknown signals that exhibit similar measured characteristics.

Deep learning examples in radio monitoring

– Convolutional Neural Networks (CNN) – analyses spectrograms to perform signal classification and anomaly detection by learning visual patterns.

– Recurrent Neural Networks (RNN) or Long Short-Term Memory (LSTM) networks – process sequential RF time-series data to uncover temporal patterns and predict signal behaviour.

– Natural Language Processing (NLP, a superset of Large Language Models/LLMs) – Leveraging Transformer-based analysis of data relationships; the resulting representations can be readily extended and applied across multiple domains that use similar data.

– Autoencoders – perform unsupervised dimensionality reduction or detect anomalies via reconstruction error.

Benefits of applying these ML and DL techniques include:

– Markedly higher accuracy in signal classification and identification under conditions of insufficient theoretical analysis.

– Automation of complex analyses that previously required extensive expert knowledge.

– Capacity to efficiently ingest and learn from massive datasets.

– Ability to discover previously unseen signal types or emerging threats.

– Enhanced adaptability to changing conditions of the RF environment.

These capabilities collectively strengthen modern automated radio-monitoring systems, providing faster, more reliable, and more insightful situational awareness. A review of Deep Learning methods applied to the cognitive radio domain that can be extended to spectrum monitoring can be found in the work of [Jagatheesaperumal *et al.*, 2025].

4.5.2.2 Supervised learning

In supervised learning, an algorithm is trained on a labelled dataset comprising input–output pairs. The algorithm's objective is to learn a mapping function that can accurately predict the correct output label for any new set of input features.

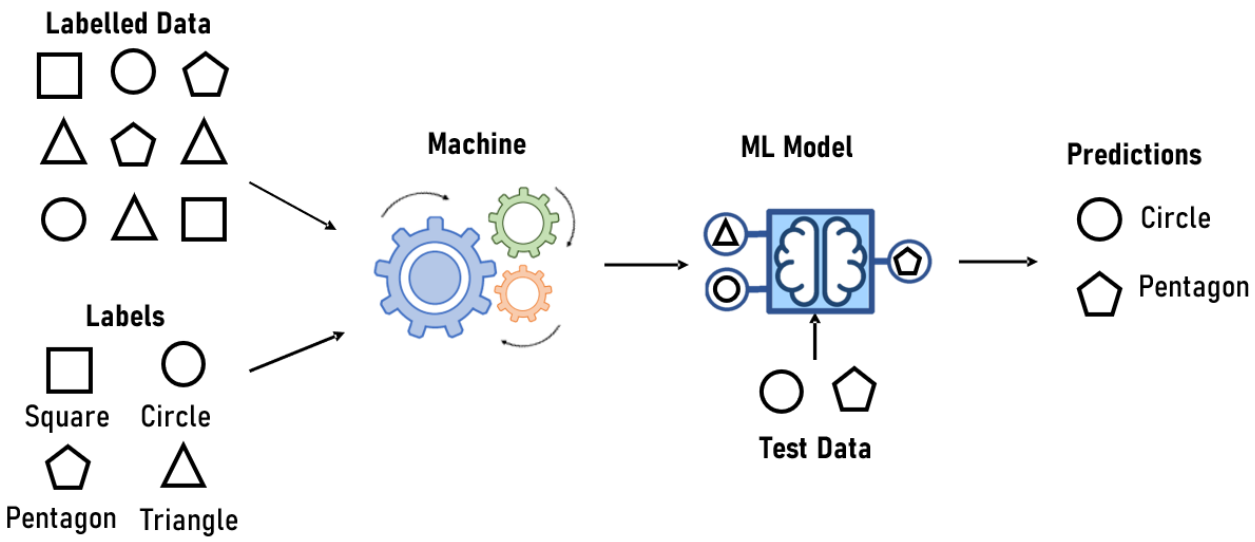
In automated radio-monitoring applications, supervised learning is indispensable when ground-truth data – signals whose type, source, or behaviour has been reliably labelled – are available. Using these references, the monitoring system can learn to recognize the distinguishing characteristics of known signal types, established interference patterns, and specific operational states. Consequently, supervised learning enables automatic identification and classification of signals or patterns for which reference data exist, supporting tasks such as:

– Verifying regulatory compliance by detecting authorized transmissions and protocols; and

– maintaining an efficient inventory of known spectrum usage.

FIGURE 4-10

Supervised learning



This approach is applied to various analytic processes in radio monitoring:

– *Signal Type Classification*: Training of classifiers using labelled datasets where each signal recording is tagged with its specific modulation type (e.g. QPSK, FM) or the radio access technology it represents (e.g. LTE, Wi-Fi, Bluetooth). Once trained, the system can automatically identify the type of newly detected signals.

– *Communication Protocol Identification*: Development of models trained on recordings of different communication protocols, each labelled with its protocol name. This allows the system to automatically recognize, for instance, whether a signal is Wi-Fi traffic, a Bluetooth connection, or a cellular transmission.

– *Specific Device Emissions Identification*: Training of classifiers with data from known devices, where the RF emissions of each device are recorded and labelled. This enables the system to identify transmissions originating from a specific type of device or even an individual emitter if the unique RF fingerprints are learnable.

Supervised learning delivers highly accurate, fully automated recognition of known signals and patterns, greatly streamlining spectrum-usage categorization. It also enhances compliance verification by automatically confirming that detected transmissions conform to relevant regulations and licenses.

4.5.2.3 Unsupervised learning

Unsupervised learning algorithms learn from data that lack predefined output labels. They uncover latent patterns, underlying structures, and intrinsic relationships within a dataset – all without explicit guidance. This approach is particularly valuable for exploratory analysis and for discovering novel or unanticipated phenomena.

In radio-monitoring applications, unsupervised learning is indispensable when grappling with the vast, largely unlabelled RF spectrum. By operating without prior knowledge or comprehensive ground-truth data, these methods can:

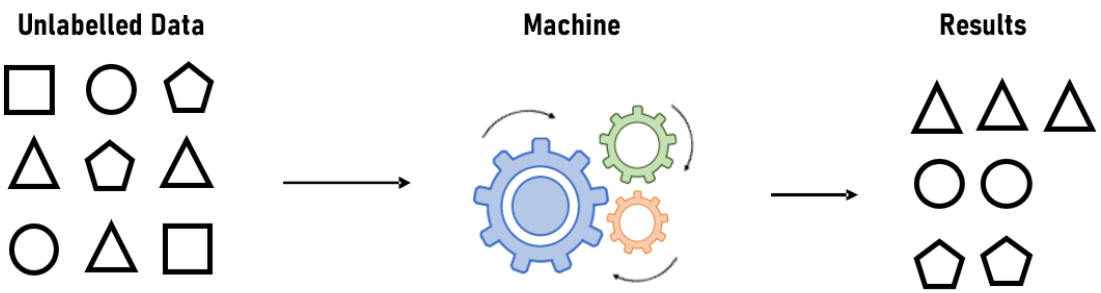
– classify previously unseen signal types.

– cluster similar signals or interference sources to reveal shared attributes; and

– identify natural groupings in spectrum-usage patterns across time, frequency, or geographical location.

FIGURE 4-11

Unsupervised learning



In radio-monitoring applications, unsupervised learning is implemented through several key techniques:

– *Clustering Algorithms*: Methods such as *K-Means* and *DBSCAN* group detected signals according to similarities in spectral features (e.g. bandwidth, spectral shape) or temporal behaviour (e.g. pulse duration, repetition rate). This grouping can reveal previously unknown signal classes or consolidate similar interference events for further investigation – even when the exact signal type is not known a priori [Czech *et al.*, 2018; Iliev *et al.*, 2017].

– *Dimensionality Reduction Techniques*: Techniques like *t-SNE* and *PCA* compress high-dimensional feature vectors into a lower-dimensional space (typically two or three dimensions). The projection simplifies visualisation, enabling analysts to spot natural clusters of similar signals and to detect outliers that may indicate unusual activity – thus supporting exploratory analysis.

Unsupervised learning enables the discovery of novel signal types and patterns, aids in identifying unknown interference sources by grouping them according to shared characteristics and delivers valuable insight into otherwise unlabelled spectrum data and usage trends. Consequently, the monitoring system gains an opportunity to expand beyond its previously defined categories.

4.5.2.4 Reinforcement Learning

Reinforcement Learning (RL) is a distinct Machine-Learning paradigm in which an agent learns to take a sequence of actions by interacting with an environment to achieve a predefined objective. Learning is guided by a reward – penalty scheme: the agent receives positive rewards for actions that advance the goal and penalties for undesirable actions. The overarching aim is to acquire an optimal policy – a strategy that maximizes the cumulative reward over time.

In radio-monitoring applications, RL is especially valuable when autonomous, adaptive behaviour is required in highly dynamic RF environments. Typical use-cases include sequential decision-making tasks such as:

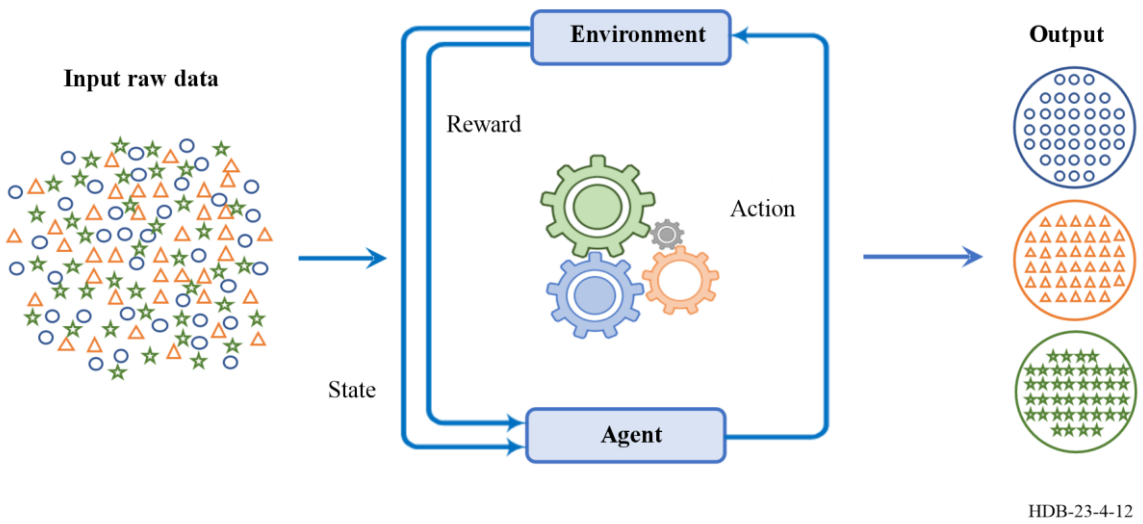
– dynamically allocating monitoring tasks among distributed sensors;

– managing radio resources in shared-spectrum scenarios; and

– enabling intelligent, rapid responses to fluctuating spectrum conditions and interference.

FIGURE 4-12

Reinforcement Learning



In radio-monitoring applications, RL can be implemented in several practical ways:

– *Optimized Monitoring-Resource Allocation*: An RL agent learns how best to distribute limited monitoring time across frequency bands or geographical areas. By observing activity patterns and receiving rewards for successful signal detections or characterizations, the agent derives a policy that prioritises scanning specific spectrum segments at optimal times, thereby maximizing the probability of detecting signals of interest.

– *Dynamic Parameter Adjustment in Cognitive Radio*: Operating within shared spectrum, an RL agent dynamically adjusts the transmission parameters – frequency, power, modulation scheme – based on real-time observations. Rewards are assigned for successful communication; penalties are imposed for causing interference. The learned policy enables the radio to coexist effectively with other users and to adapt instantly to changing spectrum-occupancy and interference conditions.

The approach delivers highly adaptive and optimised monitoring strategies that respond intelligently to complex, evolving RF scenarios. It also enables autonomous decision-making, thereby minimising the need for continuous human intervention. Furthermore, it learns optimal allocation and control policies resulting in a significantly more efficient utilisation of limited monitoring resources.

4.5.3 Application of ML techniques in Radio Monitoring

Machine Learning (ML) comprises a set of algorithms that enable systems to learn from data and to make predictions or decisions without explicit, rule-based programming. Within automated spectrum-monitoring workflows, ML techniques play a pivotal role when layered on top of traditional mathematical and statistical frameworks, especially for processing large volumes of complex, noisy RF data and for adapting to dynamically changing spectrum conditions.

By learning from observed and measured data, ML models enhance the efficiency, scalability and responsiveness of radio-monitoring systems. They support critical tasks such as signal classification, anomaly detection, interference analysis and trend forecasting.

This section introduces selected ML-based analytical techniques and representative use-cases applicable to spectrum monitoring.

4.5.3.1 Clustering

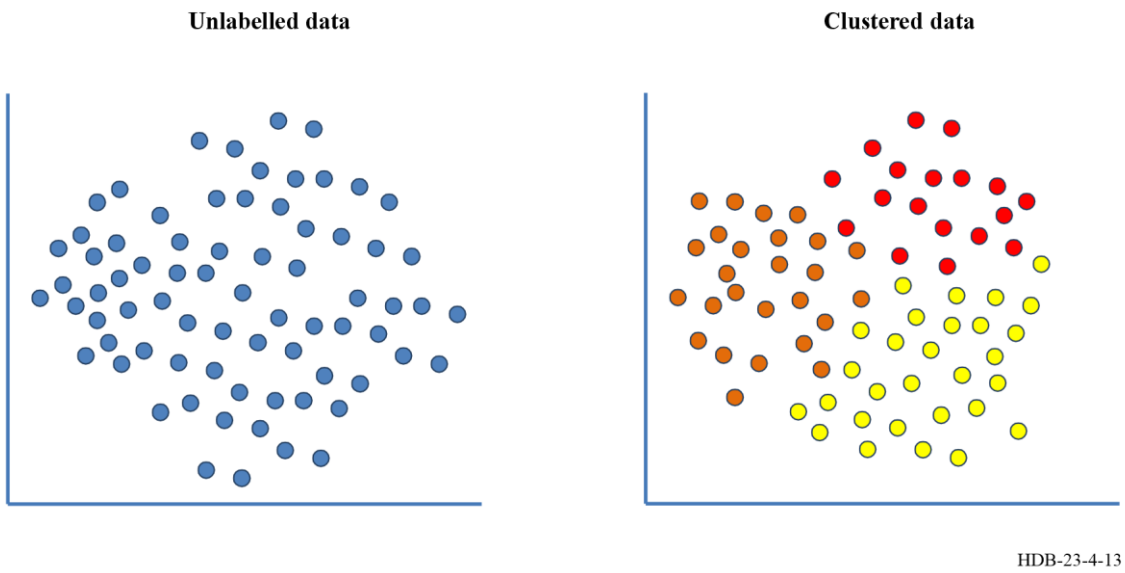
Clustering is an unsupervised-learning technique that groups similar data points according to shared characteristics. It is especially valuable for exploratory analysis when no prior labels are available.

In radio-monitoring applications, clustering enables the discovery of recurring signal patterns or emitter groups without the need for predefined classes. For example, during a wide-band spectrum survey, clustering can group previously unknown transmitters according to common signal attributes – bandwidth, centre frequency, spectral shape, modulation entropy and so forth. Analysts can then infer likely emitter types or correlate usage behaviours with geographic regions or times of day.

Typical outcomes are visualised as scatter plots or dendrograms, which display cluster membership and the relative distances between clusters, allowing the spectrum landscape to be interpreted in a more structured manner.

FIGURE 4-13

Clustering



4.5.3.1.1 Use case: grouping unknown transmitters in a wideband spectrum scan

In a nationwide wideband spectrum survey (e.g. 30 MHz to 3 GHz), the monitoring system collects I/Q samples using multiple SDR receivers placed in major urban regions. Over a 24-hour period, the system computes FFT-based power spectral density (PSD) profiles every 1 second across 1 MHz-wide segments.

The collected data is then represented as feature vectors consisting of:

– Centre frequency

– Bandwidth

– Spectral kurtosis

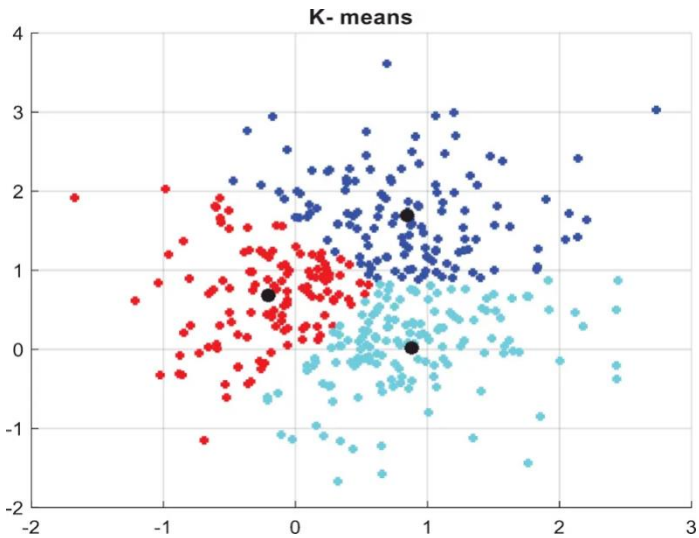
– Signal duration

– Spectral flatness or entropy.

Unsupervised clustering algorithms such as DBSCAN or K-means can be applied to these vectors. The output is grouped as the clusters that often represent recurring emitter types – such as low-power telemetry, FM broadcast, or wideband digital communication systems.

FIGURE 4-14

Example of K-means clustering



Colour-coded scatter plots showing cluster memberships across the time-frequency domain, enabling analysts to infer usage behaviour and possible emitter identification without prior labels.

4.5.3.2 Regression

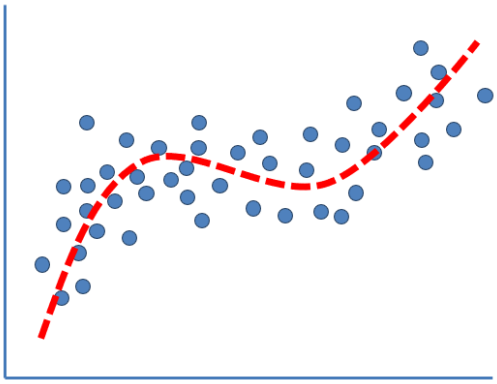
Regression analysis is a supervised-learning technique that models the relationship between a dependent variable and one or more independent variables, with the primary goal of predicting continuous numeric values.

In radio-monitoring applications, regression methods are widely used to estimate radio-propagation path-loss as a function of terrain, distance, and frequency band. For example, a linear-regression model can predict the decay of signal strength with distance in VHF bands under clear-sky conditions. More advanced approaches such as polynomial regression or support-vector regression (SVR) can incorporate multipath effects and terrain masking.

Visual diagnostics, including regression curves and residual plots, help assess model accuracy and deviations from expected behaviour. These predictive models assist spectrum managers in forecasting interference levels, optimising antenna deployment, and estimating channel availability over time.

FIGURE 4-15

Regression



4.5.3.2.1 Use case: predicting interference level in an industrial zone

A fixed monitoring station near an industrial complex makes logs of the received signal strength (RSSI) in the 400-470 MHz UHF band. Historical logs show fluctuation in signal power depending on equipment operation cycles in the area.

A polynomial regression model is trained using:

– Time of day (hour index)

– Day of the week

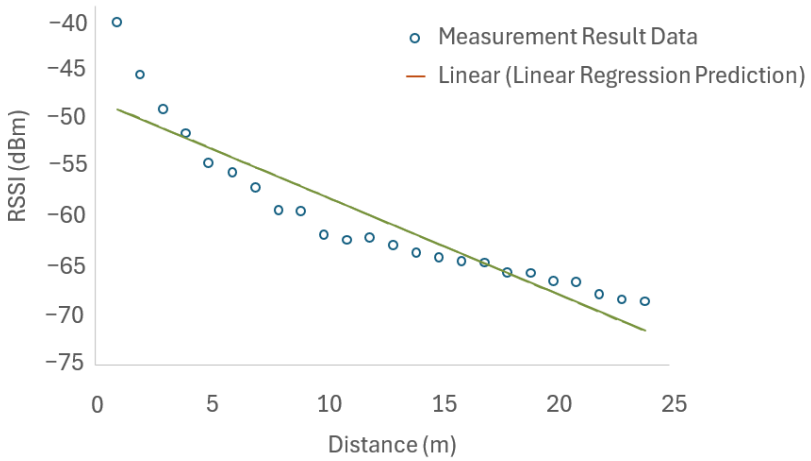
– Historical average RSSI

– Temperature/humidity (from external sensors).

The model predicts hourly RSSI trends 24 hours in advance. Maintenance crews use this prediction to avoid scheduling critical sensor transmissions during interference peaks.

FIGURE 4-16

Comparison of RSSI measurement and regression prediction [Rifki *et al.*, 2024]



Overlay plots of predicted versus observed RSSI trends, plus confidence intervals indicating forecast reliability.

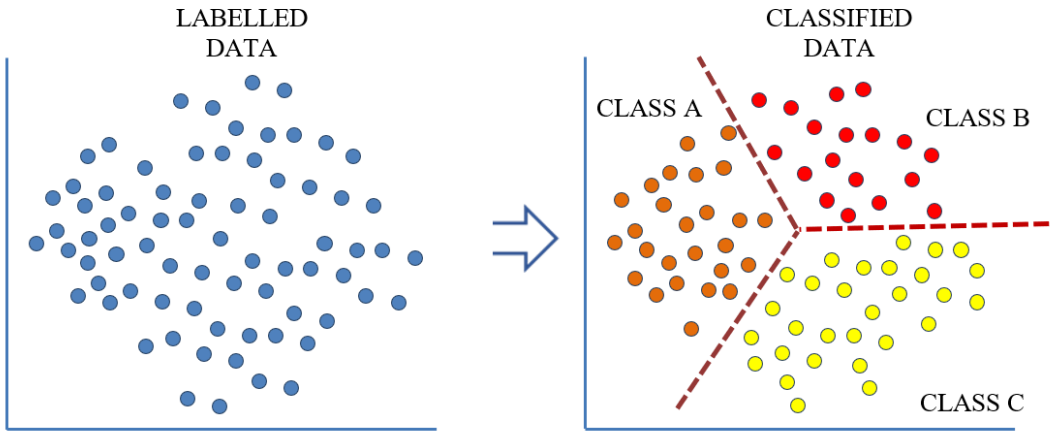
4.5.3.3 Classification

Classification algorithms assign incoming data to one of several predefined categories based on patterns learned during training. This is a core function in automated signal recognition and multiple algorithms have been developed with most recent research exploring different architectures of neural networks and learning strategies [Boegner *et al.*, 2022; O'Shea *et al.*, 2018; Oh *et al.*, 2025; Tan *et al.*, 2025; Vallance *et al.*, 2024]. In regulatory enforcement scenarios, classification may also be used to identify unauthorized transmissions based on the unique signature of the signal.

The confidence of the result is dependent on SNR and is usually depicted as a set of confusion matrices showing true versus predicted classes (Fig. 4-19), or decision boundary visualizations that illustrate how well the model separates categories (Fig. 4-17).

Use case in subsection 4.5.3.3.1 presents a common scenario, where a dataset that might include human made classification is used to train a model with either classical ML algorithms or neural networks through DL.

FIGURE 4-17



4.5.3.3.1 Use Case: automatic modulation classification (AMC) for spectrum enforcement

There is rich literature on ML and DL techniques for the classification of known modulation types [Jafarigol *et al.*, 2025; Jassim & Khider, 2022; Tian *et al.*, 2026]. The results indicate that the recognition accuracies of deep learning methods – including Deep Neural Networks (DNN), Long Short-Term Memory (LSTM), and Convolutional Neural Networks (CNN) can accurately identify more than 80% of the signals even down to 0dB SNR, achieving more than 95% accuracy with SNR above 8dB. In contrast, machine learning methods such as Support Vector Machines (SVM), K-Nearest Neighbours (KNN), and Random Forests (RF) have accuracies in the range of 40 to 70%. Figure 4-18 illustrates a typical application of these techniques for the classification of known modulation types.

The confidence level achieved by the AMC is represented by confusion matrixes, where the probability of correctly inferring the modulation (horizontal axis) is plotted against the actual known modulation as presented in Fig. 4-19.

For classification tasks, traditional ML methods rely on extracted features, whereas DL models are capable of automatically extracting features from raw or minimally pre-processed I/Q data. As the number and complexity of modulation schemes increase, DL-based methods generally maintain higher recognition accuracy and robustness than traditional approaches.

Integrating AMC into the spectrum monitoring workflow, signals with unexpected modulation in licensed service bands (e.g. BPSK in FM radio band) can be flagged for further inspection using real-time dashboards with signal labels, confidence bars, timestamps, and alerts for suspected violations.

FIGURE 4-18

Block diagram of modulation classification based on ML and DL

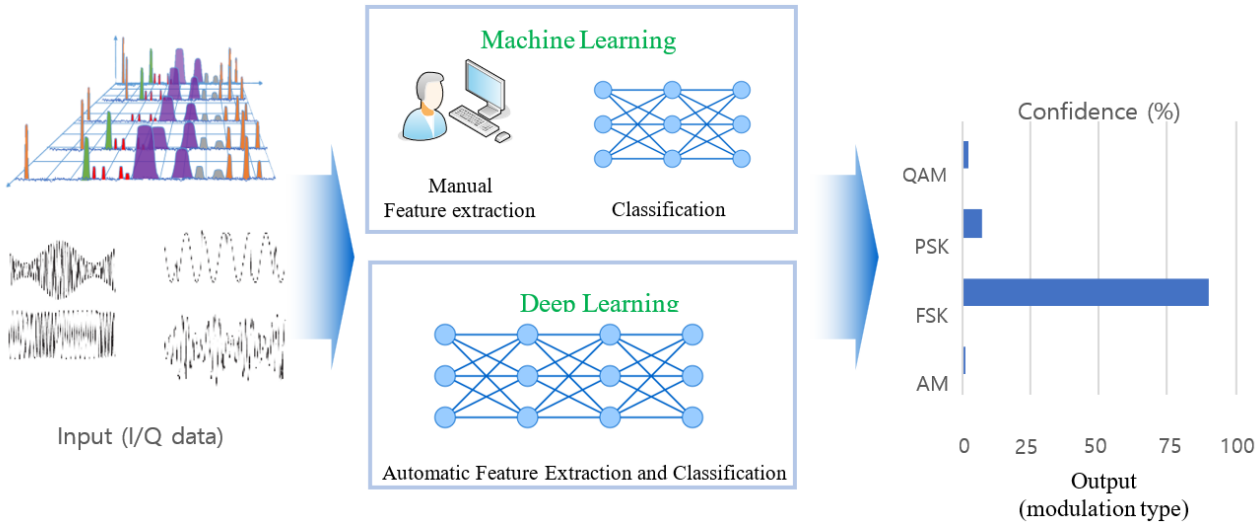
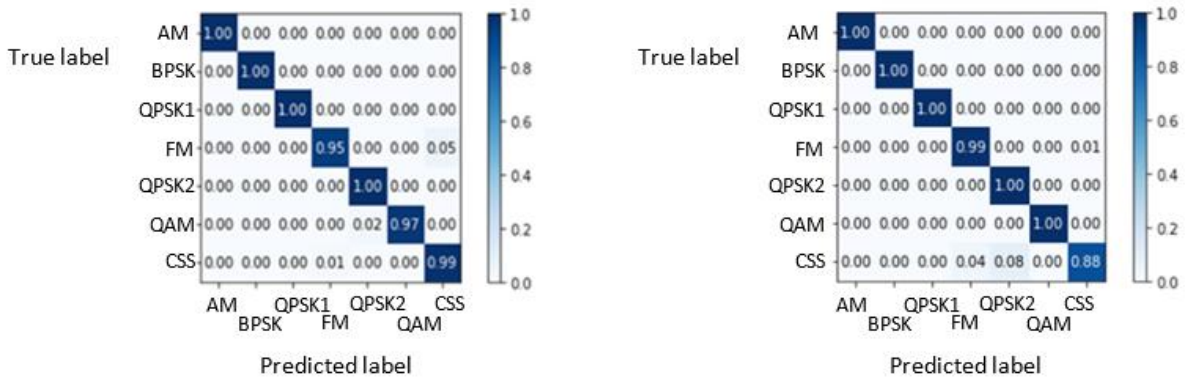


FIGURE 4-19

Normalized confusion matrix for modulation classification example



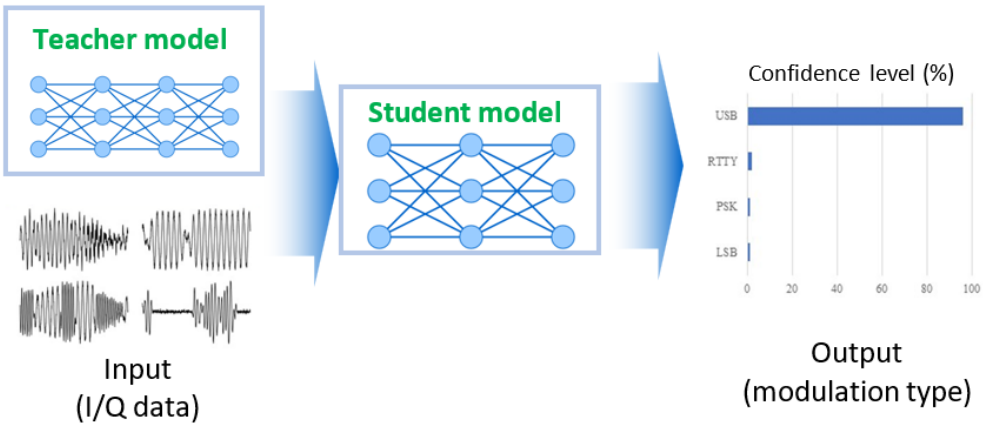
(a) Deep Learning (b) Feature-based Machine Learning

DL–based modulation recognition typically requires large training datasets and substantial computational resources, which could limit its direct deployment on resource-constrained spectrum monitoring infrastructure. To address this practical constraint, a spectrum monitoring system can employ knowledge distillation (described below) to transfer the capability of a high-capacity model to a lightweight model, enabling efficient modulation recognition on receivers with embedded computing and storage capabilities used for edge processing.

Figure 4-20 presents a case study verifying the effectiveness of knowledge distillation in modulation recognition, in which high-capacity DL models, including Deep Convolutional Neural Networks, are employed as teacher networks, and lightweight models such as Convolutional Neural Networks (CNN) serve as student networks. During this process, the student model is trained on merely 1% of the full training dataset while learning both the output probability distributions and intermediate-layer features from the teacher models. The results indicate that after knowledge distillation, the student model achieves an 8.15% accuracy improvement compared with the pre-distillation baseline; for instance, the classification confidence for Upper Sideband (USB) signals increases from 91% to 96%. Simultaneously, the student model reduces floating-point operations by 99.7% relative to the teacher models [Yao *et al.*, 2025].

FIGURE 4-20

Block diagram modulation classification via knowledge distillation



4.5.3.4 Anomaly detection

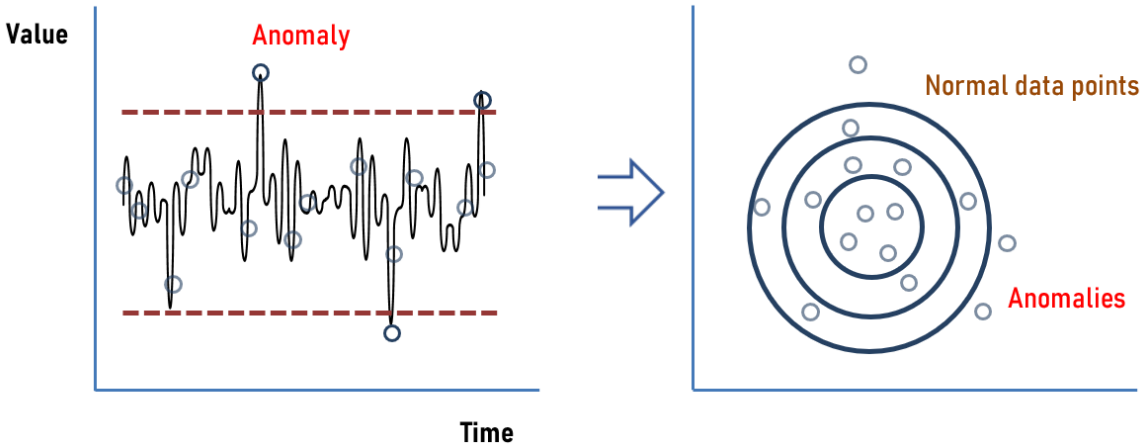
Anomaly-detection techniques identify data points that deviate markedly from expected behaviour. In radio-monitoring applications, they are invaluable for flagging unforeseen signals – such as jamming, spoofing, or unauthorised transmissions – that appear without prior labelling.

For instance, an autoencoder neural network can be trained on "normal" signal profiles from maritime communication bands (e.g. AIS and DSC). In operation, any spectrogram that yields a high reconstruction error is flagged as anomalous, thereby triggering alerts for human analysts or automated counter measures.

Typical visual outputs include time-series plots with anomalous spikes and t-SNE projections that highlight outlier clusters.

FIGURE 4-21

Anomaly detection



4.5.3.4.1 Use Case: detecting jamming signals in the GNSS L1 band

In the 1 575.42 MHz GNSS L1 band, a continuous monitoring station logs spectrogram data. Under normal conditions, only satellite signals and weak sideband emissions are observed.

An autoencoder model is trained using 1 month of "clean" data. During operation, spectrograms are fed into the model, and reconstruction error is computed.

Anomalies are flagged when:

– Reconstruction error > 3σ threshold

– Sudden high-energy burst appears in time-frequency region

– Spectral shape deviates from known GNSS patterns.

Real-time alert dashboard with spectrogram visualizations showing the anomaly location and confidence score.

4.5.3.4.2 Use Case: Foundation model enabled spectrum anomaly detection

Traditional rule-based or shallow learning methods, which typically rely on small-scale models, are primarily designed for specific tasks and narrowly defined tasks. These approaches generally lack the ability to adapt to unseen environments and, therefore, often fail to address the diversity and unpredictability of spectrum anomalies in dynamic and complex scenarios. To overcome these limitations and enhance anomaly detection, more advanced AI techniques are required.

This objective can be achieved through the adoption of foundation model techniques – a large-scale ML model serving as the foundational basis for a wide range of downstream tasks [Zhou *et al.*, 2025]. The core principle is that foundation models are pre-trained on massive and diverse datasets, enabling them to learn general-purpose representations that are highly versatile and adaptable across multiple domains and tasks. Compared to traditional approaches, foundation models offer superior robustness, scalability and transferability, making them particularly well-suited for the challenging and evolving landscape of spectrum anomaly detection.

This use case employs a unified encoder-decoder foundation model for spectrum anomaly detection. The model integrates feature extraction, representation learning, and anomaly classification within a single architecture.

– Input: Raw spectrum data based on I/Q samples.

– Output: The detected jamming/abnormal signals and behaviours.

By leveraging the powerful representation capabilities of foundation models, this approach could significantly improve the detection of unknown or complex anomalies, thereby providing a higher level of intelligence and automation for spectrum monitoring. This use case illustrates possibilities which are not minimum operational requirements.

4.5.3.5 Prediction

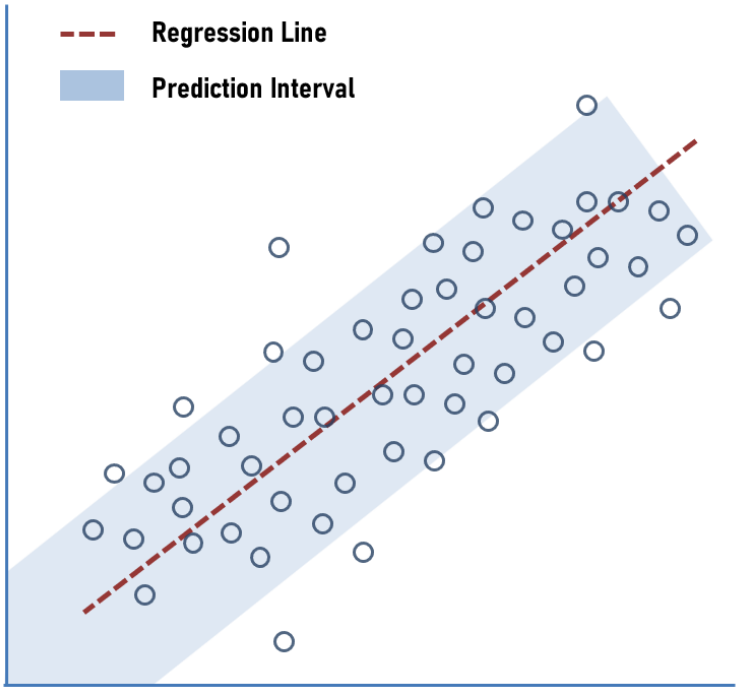
Prediction models use past data to estimate future signal behaviour or spectrum states, enabling proactive monitoring and strategic spectrum planning.

In practice, long short-term memory (LSTM) networks can forecast future frequency band occupancy based on historical usage data. For example, in a metropolitan setting, an LSTM model may predict periods of congestion in particular frequency bands, thereby allowing regulators to schedule monitoring resources dynamically or to plan targeted enforcement.

Performance is typically evaluated with time-series plots that compare predicted and actual occupancy levels, providing evidence for policy and operational decisions.

FIGURE 4-22

Prediction



4.5.3.5.1 Use Case: Forecasting future spectrum occupancy in the LTE band

An agency wants to predict when the 1800 MHz LTE band will be congested in a metro area. Using historical occupancy logs (1-minute resolution), an LSTM neural network is trained to learn temporal patterns in band usage.

Input features include:

– Past occupancy ratios (last two hours).

– Time of day, day of week.

– Cell tower ID (one-hot encoded).

The model forecasts occupancy for the next 60 minutes. When predicted occupancy exceeds 80%, it triggers proactive reallocation or monitoring adjustments.

Interactive chart of real versus predicted occupancy, with color-coded risk bands (green: normal, red: predicted overload).

4.5.3.5.2 Spectrum map construction using embodied intelligence

To evaluate network performance in complex environments, anticipate coverage gaps, and plan cost-effective deployments, operators could construct a three-dimensional (3D) spectrum map. This represents a typical application of utilizing historical data to predict signal behaviour or spectrum states.

This objective could be achieved by employing embodied intelligence, which refers to AI systems deployed on aerial platforms [Diao *et al.*, 2026; Li *et al.*, 2025]. By collecting a limited number of radio samples using aerial platforms, it becomes possible to intuitively visualize the precise localization of signal sources and the continuous representation of signal power levels through a 3D spectrum map.

Input features include:

– Measured signal strength.

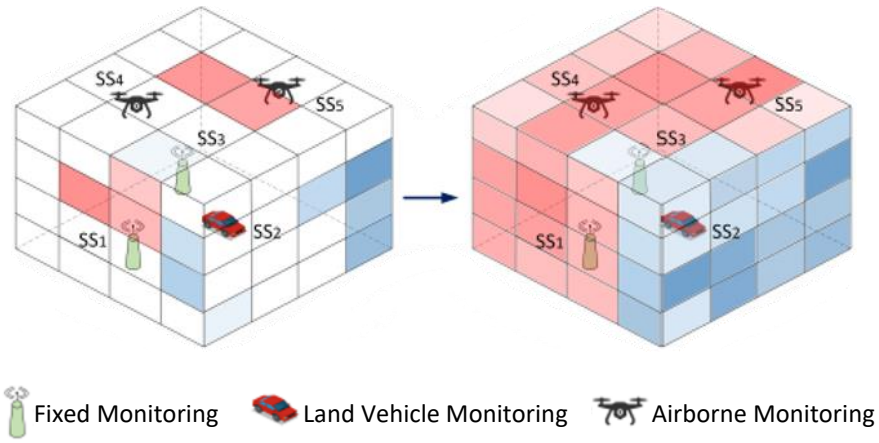
– Locations of measured signals.

– Frequency and time information of measured signals.

As illustrated in Fig. 4-23, the left cube shows the measured signal strength from limited samples in 3D space (where different colours represent varying strengths and white grids denote areas with no measurements). The right cube depicts the spectrum map constructed using embodied intelligence, where previously unmeasured grids (represented by white grids) have been filled with predicted results (represented by non-white colours). This construction of the spectrum map effectively bridges the gap between sparse measurements and comprehensive spatial characterization of the radio environment, enabling the estimation of the spectrum usage characteristics across the 3D space.

FIGURE 4-23

Spectrum map construction result and signal strength prediction



4.5.3.6 Angle-of-arrival (AoA) estimation and enhancement using ML

Direction-finding (DF) represents a primary operational task within radio monitoring for which classical methods are detailed in section 5.7 of this Handbook. ML algorithms have been employed using different approaches, either as an alternative method or by complementing classical methods by adding processing stages or optimizing parameters to improve AoA estimation performance [Elbir, 2020; Jenkinson *et al.*, 2023; Merkofer *et al.*, 2024; Nguyen *et al.*, 2024].

4.5.3.6.1 Use Case: ResNet-based pseudo-MUSIC AoA estimation

The following Figures illustrate an application of combined ML and classical DF methods. In this example, a ML initial stage (ResNet-based) is trained to generate the data to be used by the classical DF algorithm stage (pseudo-MUSIC) to optimize the DF result as depicted in Fig. 4-24. Both alternatives, using only MUSIC and the combined method, were evaluated using I/Q data collected from a Uniform Circular Array (UCA) under practical field conditions. The comparative analysis is presented in Fig. 4-25 and demonstrates that the combined approach can provide improvement in DF accuracy, especially under low SNR values depending on the ResNet model used (ResNet-8 to ResNet-34).

FIGURE 4-24

Diagram of Machine Learning-based combined AoA estimation

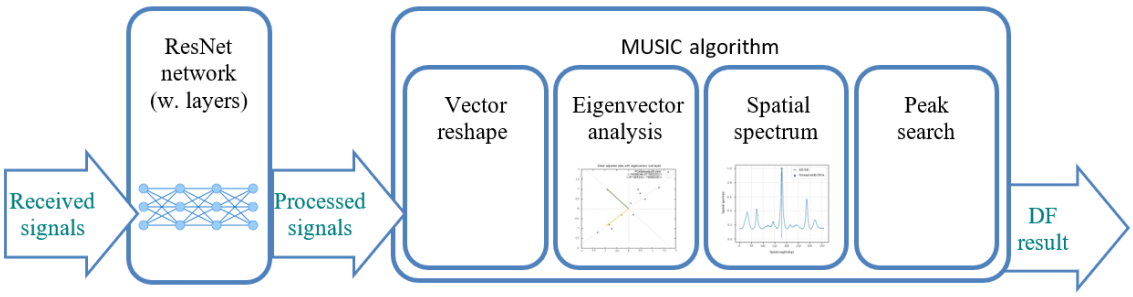
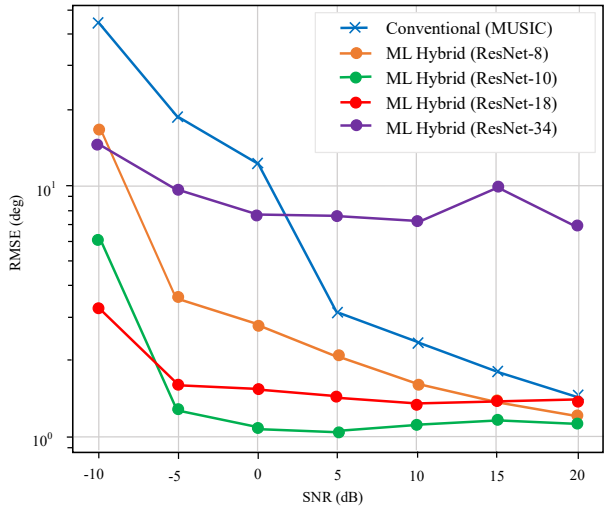


FIGURE 4-25

Performance comparison of conventional, ML-based combined AoA estimation



4.6 Data usage and intelligent interaction

Once data has been gathered and processed as described in the previous sections, further analysis and processing will generate the desired results and products of the spectrum monitoring process. Such processing aims to ratify the results before publishing and sharing as an official report. It can also be used to complement previous analysis and rectify misclassifications to improve the models and algorithms applied in the preceding stages.

Spectrum monitoring engineers and technicians often employ specialized applications like those used for interactive operation to perform post processing because of the greater flexibility in terms of processing power and time that are possible when stored data is always accessible.

The following sections take a deeper look into the final stages of transforming data into knowledge and discuss some different visualization and control mechanisms that can interact with the information to make it useful to the spectrum management process.

4.6.1 Human–machine interaction and usability standards

Most organizations do not develop their own software and use commercially available solutions not optimized to their intended operational conditions. It is important, however, that the selection of a solution takes into consideration good practices for the development of Graphical User Interface (GUI) and well-established usability principles. Understanding these concepts is critical to develop a more acute perception about software quality and thus enable the selection of alternatives with a better user experience (UX), resulting in lower training costs, better acceptability of the solution by users, and reduced operational errors.

An increasing number of solutions are configurable and enable users to modify the default interface to align with personal, organizational, and cultural requirements. An example is the dynamically configurable dashboard, where users can create presentation styles and screen organizations using pre-defined interface components.

There are many recommendations and principles that orient the design of user interfaces. These generally indicate that acute sensibility and perception regarding human behaviour are needed by its practitioners.

Large software providers usually publish guidelines that enable developers to create a visual identity that users associate with their companies. Many of these guidelines are made public and free to orient software engineers from different companies to design their own applications that may be seamlessly integrated with an OS or software ecosystem.

There are also standards such as ISO 9241 [ISO, 2019] that provide guidelines to support human-centred design for interactive systems. This specific ISO standard is intended to be used throughout the entire software life cycle by those managing design processes. It provides useful references for the development and evaluation of interactive spectrum monitoring data collection systems.

Design standards usually include the definition of design elements such as colour pallets, typography, spacing, grid layouts, icons, menus, background images or focus states. Other elements such as controls and visualization components may also be defined.

The user experience will be improved if the application interface follows a user-centric design approach with known features including classical gestalt principles such as similarity, continuity, symmetry, and order. These principles often point toward guidelines used by major software manufactures to create interfaces that conform to common practice in terms of the placement of controls and displays.

Principles such as KIS (Keep it Simple) are not always followed but are essential to shorten the application learning curve and improve acceptance across a diverse user base.

When considering usability standards, there is no single metric that enables the selection of a proper software solution. However, a series of qualitative and quantitative methods may be used to evaluate or compare different solutions for given task conditions. In this case, a set of defined metrics may be used, such as success rate, average time on task (ToT), number of errors or learnability.

In general, the look and feel of spectrum monitoring applications should not depart far from other standard computer applications in use. Previously, software interfaces mimicked the equipment's front panel mechanical controls such as buttons and knobs (as shown in Chapter 3); and concepts such as touch screen and 3D visualization were not yet developed. Commonly used control and display features include select and combo boxes, text fields, slide bars and graphical selections with features such as zoom, pan, orbit with the aid of point, area, and volume markers.

Commands via live audio and/or video are not common in off-the-shelf spectrum monitoring solutions, but such interfaces may enable better accessibility for specialized monitoring tasks and conditions.

Monitoring result displays may include audio, text, and graphs with one dimension (power level bar graphs), 2D (e.g. panoramic or spectrum displays of power versus frequency, power versus time, and histograms), and 3D (e.g. signal amplitude versus frequency versus time).

To enable visualization of 3D content on a 2D display, the solution may either provide a fixed projection, such as traditional spectrograms where the power level is represented by a colour scale and the time-frequency axes are plotted at a 90-degree angle, or an adjustable projection sometimes called a waterfall graph.

User interactions with the displays are necessary to configure the receiver by entering search parameters or recalling previous configurations and display setups. They are also needed to adjust the spectrum sweep rate and sampling time to enable visualization of a band smaller or larger than the receiver IBW by zooming in and out around a frequency of interest. Also, spectrum markers are useful for manual measurements and observations of one or more signals.

Response time of the spectrum monitoring equipment and software is a controversial topic. Available studies [Dabrowski et Munson, 2011] show that for continuous and instantaneous interaction such as typing, mouse pointing and clicking comfort, user interactions require response times on the order of 50 to 200 ms. If the system response time becomes more than 10 to 12 seconds, users typically become impatient and question the

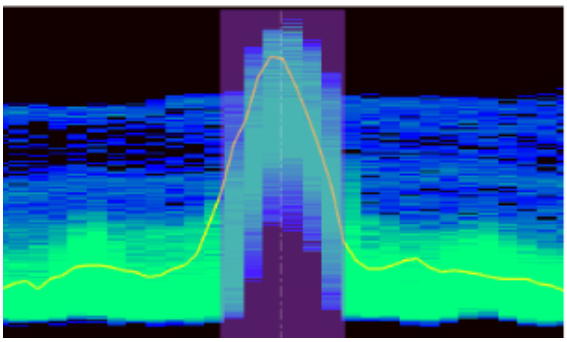
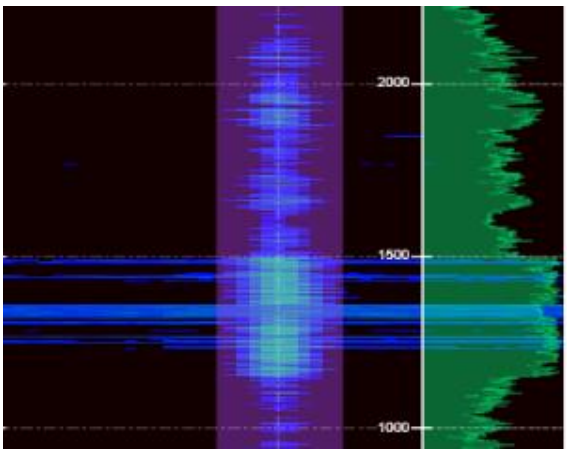
operational condition of the system. This is critical when continuous adjustment of the acquisition parameters is required, and for conditions when response times on the order of seconds may render the monitoring system unfit for the task, e.g. performing geolocation with TDOA and AOA systems.

4.6.2 Visualization and decision support

Visualization tools translate complex measurement data into representations that can be intuitively understood. Typical visualizations used in spectrum monitoring are presented in the following summary.

TABLE 4-3

Typical visualizations used in spectrum monitoring

	Spectrum power as a function of the frequency. This classical spectrum analyser equivalent display, also known as a spectrum plot or spectrum trace, enables the visual identification of emissions on the receiver noise floor. It may be enhanced by multiple overlapping plots representing different values, such as averages, minimum or maximum over a time interval, or features such as persistence (phosphor display), which provides operators with an intuitive view of persistent, intermittent and transient signals within the observed frequency band.
	Spectrum power as a function of time, as indicated on the right side of this image, can be better understood when displayed along with the spectrogram (left side). This provides a clear understanding of the time behaviour or dynamics of an emission.
	Received signal strength as a function of location is observed in drive-test operations, where the RF power level is represented by a colour scale and displayed on a map. This sort of presentation can be generalized and used with any other measurement quantity evaluated, such as direct indication of service quality, emitter location from TDOA, or AOA from a DF system, as presented in Chapters 3 and 5.

Combinations of these basic presentation elements along with propagation tools, as discussed in Chapter 7, can be used to create a rich interface for planning and data analysis, as illustrated in Figs 4-26 to 4-28 that show examples of available solutions.

FIGURE 4-26

Measurement data catalogue webpage and detailed results

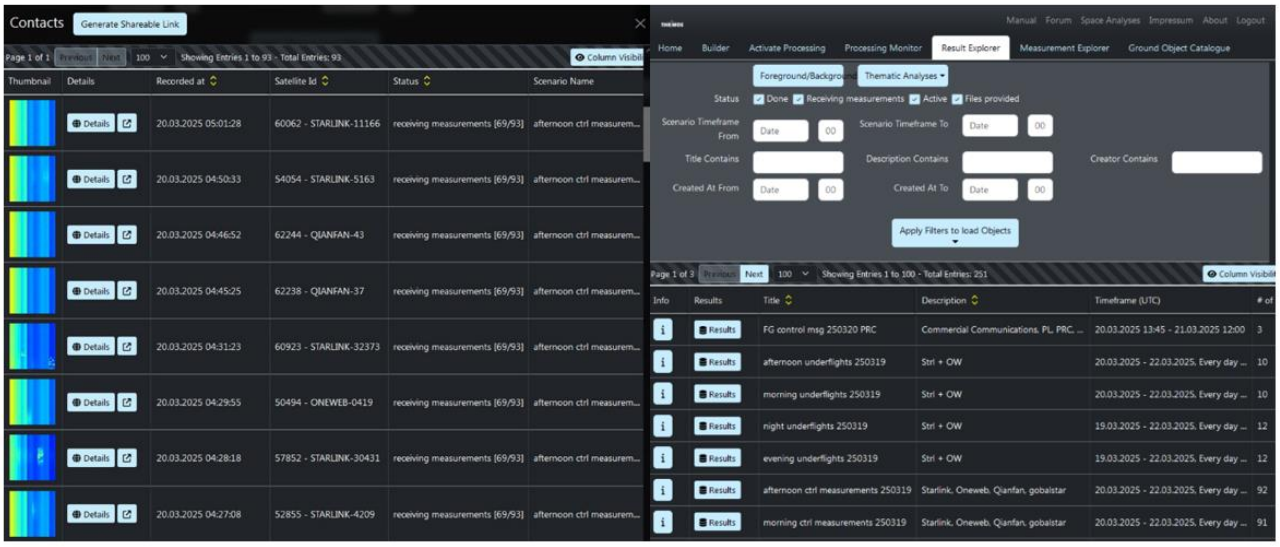
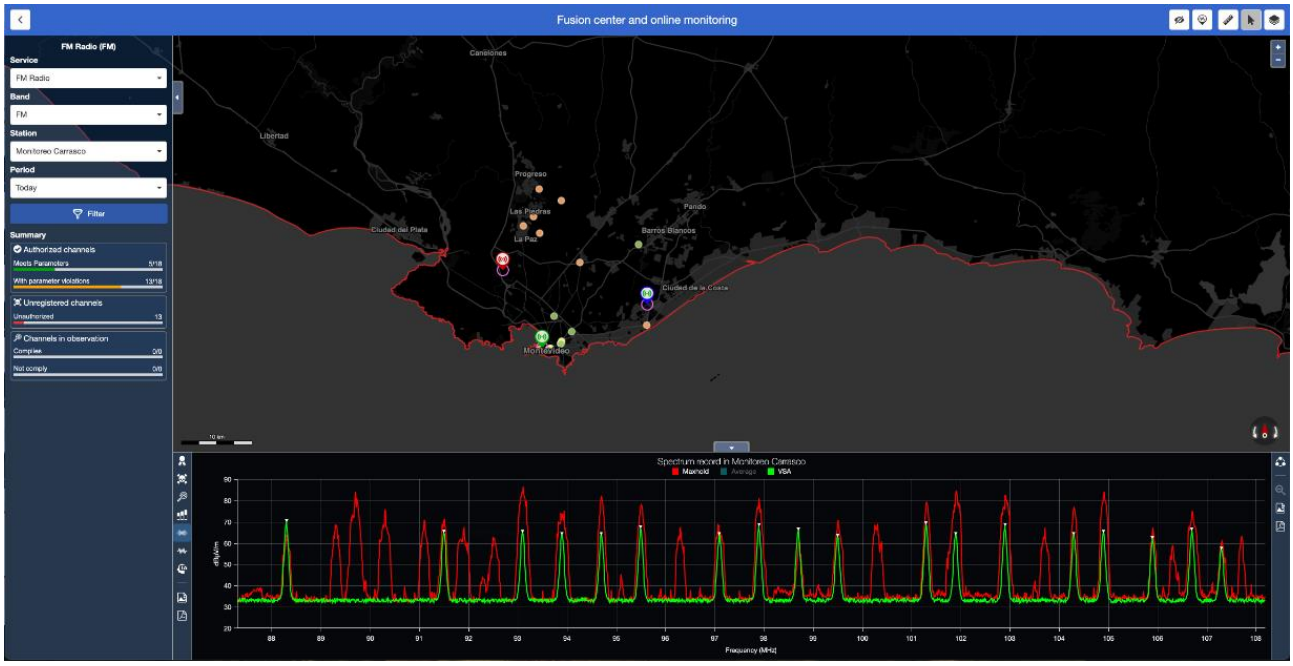


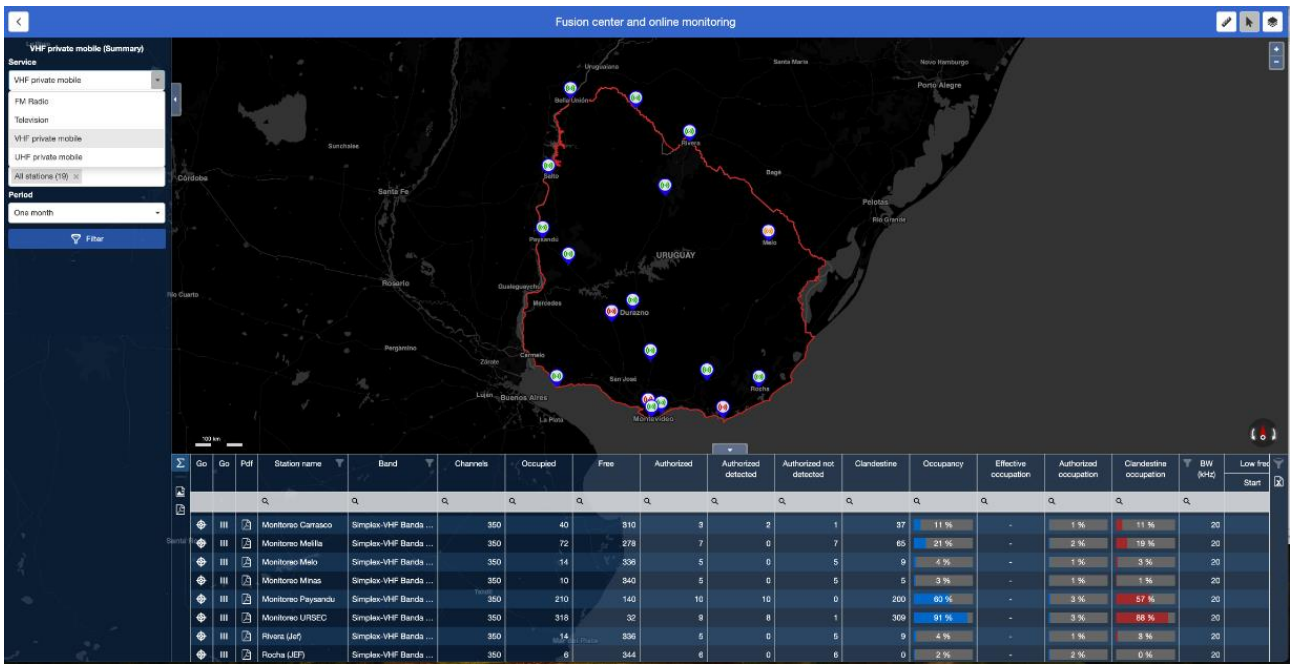
FIGURE 4-27

Coverage area estimates along with population data information

FIGURE 4-28

Measurement data presented along with estimated data from license database





The interactive displays, as presented in the Figures above, can be integrated into a document production workflow to create static reports that make the information accessible to different parts of the administration and through different communication channels. More importantly, the interfaces can be part of a comprehensive spectrum management solution, incorporating RF models and propagation tools that enable the creation of Digital Twins of emitters, improve anomaly detection [Schösser *et al.*, 2025], and enhance other system functions.

Using a diverse set of controls and visualizations, spectrum monitoring data can be shared and published for the intended audience and level of confidentiality:

– Direct access to internal stakeholders through specific applications, either desktop or web based.

– Exchange between administrations, which may follow standardized ITU formats, such as Recommendations ITU-R SM.2117, ITU-R SM.1809, ITU-R SM.1393.

– Publication via web portals or APIs, allowing real-time or near-real-time access for authorized stakeholders.

– Integration with open-data portals, where non-confidential datasets can be published for public use, supporting transparency and research.

The adoption of each of these methods is dependent on the data policies defined by the administration which may require appropriate access controls including encryption and audit logging for sensitive data.

4.6.3 AI-augmented data usage

While the core principles of measurement, data acquisition and management remain stable, advances in automation, AI, and large-scale data processing are transforming how monitoring systems are being designed, deployed and operated.

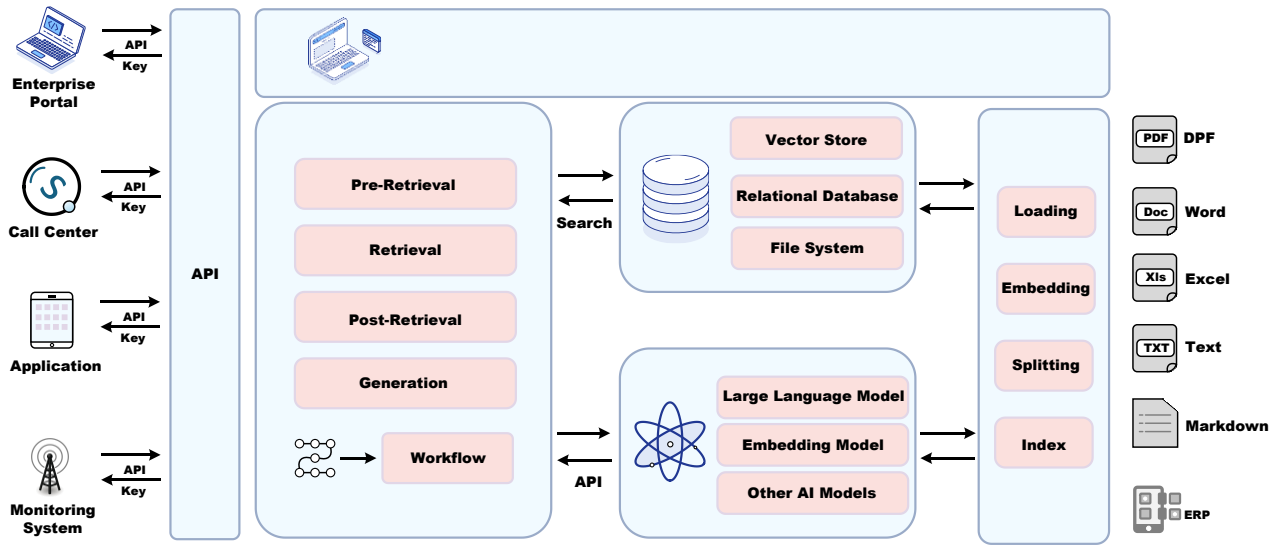
Referring back to Fig. 4-2 and the concepts presented in the beginning of this Chapter, the introduction of more capable analytical systems into the spectrum monitoring workflow may improve signal processing, emission detection, automated classifiers and anomaly-detection algorithms, as discussed in § 4.5. Also, they will surely affect the interaction between operators, equipment and data, enabling new ways to search, analyse and act on monitoring information.

With the advancement of AI, large language models (LLMs) and brain-inspired intelligence are emerging as key trends in automation and data-management applications [Qu *et al.*, 2025]. These technologies provide new means for integrating heterogeneous data sources, automating workflows, and enabling natural-language interaction with complex datasets.

Figure 4-29 illustrates an LLM-based framework for automation and data management. On the right side, private data sources are represented, including radio-management regulations and databases; on the left side, communication-related services such as enterprise portal, call centre and other applications are shown. These services are integrated through Application Programming Interfaces (APIs), including the spectrum monitoring system responsible for receiving and processing radio spectrum data, I/Q data, decoded data, etc. Under the support of an LLM, the system realizes automation and data management tasks across these diverse resources.

FIGURE 4-29

LLM-based framework for automation and data management



To position this figure with practical implementations, three AI patterns are discussed in §§ 4.6.3.1 (Stand-alone), 4.3.6.2 (Retrieval-Augmented Generation), and 4.6.3.3 (Reason and Act). Section 4.6.3.4 describes Model Context Protocol and Agent to Agent interactions adding information on communications and coordination internal to an AI pattern. Section 4.6.3.5 describes a use case for radio monitoring coverage prediction based on LLM.

4.6.3.1 Stand-alone LLMs (Prompt-only)

A stand-alone large language model (LLM) used in prompt-only mode is an AI system that generates responses based solely on the information encoded in its training parameters. The model takes a natural-language prompt from the user and produces text by drawing on patterns it has learned from vast amounts of publicly available data. This approach allows rapid prototyping and natural-language interaction, making it useful for drafting reports, explaining technical concepts, or providing general guidance.

Stand-alone LLMs operate in isolation: they cannot directly access proprietary or up-to-date information unless explicitly included in the user's prompt. Their knowledge is also limited to the data available at the time of training, and they cannot take actions beyond generating text. As a result, while they can provide broad coverage of concepts and intuitive explanations, they may also produce outdated or unverified outputs (plausible but unverifiable statements combined with hallucination risk).

In spectrum monitoring contexts, their role is mainly supportive offering language assistance rather than authoritative or operational analysis. Therefore, it can be used to draft text reports and expand concepts presented by the user using distinctive styles. For example, it could draft responses to inquiries by the general public.

4.6.3.2 Retrieval-augmented generation

Retrieval-Augmented Generation, mostly referred only by the acronym RAG, enhances a stand-alone LLM by supplying external, up-to-date information at the time of answering. The query is first used to search relevant document collections, such as monitoring archives, regulatory databases, or technical manuals, and the retrieved information is then provided to the LLM as context for generating the response. This ensures that the model's outputs are grounded in authoritative sources rather than relying solely on the knowledge embedded in its training parameters.

It is particularly valuable for integrating proprietary or national information into AI-assisted workflows, improving transparency and enabling responses that cite their evidence. Its effectiveness depends on the quality of the retrieval layer (indexes, embeddings, metadata) and the governance of the source material.

In spectrum monitoring applications, Retrieval-Augmented Generation can be used to generate textual reports with analysis supported by relevant measurement results and evaluate them in the context of the current regulatory framework, licenses and national allocation tables.

At the time of publication of this edition, Retrieval-Augmented Generation is evolving into new forms of knowledge organizations tailored to optimize the agentic operation with promises of increased efficiency and new forms of data architecture that moves away from traditional vector databases engines.

4.6.3.3 Reason-and-Act (ReAct)

The ReAct framework extends simple question-answering by enabling LLMs to alternate between reasoning steps and concrete actions. For example, it can move from querying a database to launching an analysis task or invoking an external application. Instead of producing text passively, the model plans and executes sequences of tool calls, recording its reasoning and results at each stage. This creates transparent, traceable workflows that combine language-based inference with practical automation.

ReAct is well-suited to environments where the workflows involve multiple steps and data sources. For example, a ReAct-based assistant could receive a request to improve the fidelity of a digital twin representation for emitters in a specific service. In response, it could automatically schedule a measurement campaign or retrieve recent spectrum data, run occupancy analyses, access geospatial layers and propagation tools, compare the results, and prepare draft reports, leaving final review and approval to the operator.

To use ReAct, it is essential to have a strong tooling layer foundation through open APIs for data access and job orchestration. Also, security and governance mechanisms are needed such as Role-Based Access Control (RBAC), a policy constraint to bound the integration of spectrum monitoring services into the AI framework.

4.6.3.4 Model Context Protocol (MCP) and agent-to-agent interaction

Recent developments in AI-assisted systems have highlighted the importance of structured interaction between large language models (LLMs) and external data sources, tools and services. The Model Context Protocol (MCP) is an emerging architectural approach that defines a standardized method for supplying contextual information and controlled tool access to AI models during execution.

In contrast to prompt-only interaction models, where the LLM operates exclusively on user-provided text, MCP-enabled systems allow the AI model to dynamically access structured data repositories and services, such as receivers, measurement results, spectrum management databases, observability platforms and automation services through well-defined interfaces. This approach improves reliability, traceability and governance of AI-generated outputs by ensuring that responses are grounded in authoritative and up-to-date operational data.

Within a spectrum monitoring environment, MCP-like architectures may enable:

– Controlled querying of measurement archives and metadata catalogues.

– Secure interaction with spectrum management systems for license verification.

– Invocation of analytical functions such as occupancy calculation or anomaly detection.

– Generation of structured regulatory reports based on validated datasets.

By separating the language reasoning component from the operational tool layer, MCP supports modularity, interoperability and auditability. It also facilitates the enforcement of cybersecurity policies, access control mechanisms and logging requirements, which are critical in regulatory environments.

In complex environments, such as a spectrum monitoring network where multiple processes may employ independent AI Agents, additional mechanisms may be used to enable interaction between multiple AI-based entities, often referred to as agent-to-agent (A2A) interaction. While MCP governs how an individual agent accesses external context and services, A2A approaches define how multiple agents communicate, coordinate tasks and exchange information within a system. Classical approaches such as those based on the FIPA Agent Communication Language (ACL) define structured message types and interaction patterns to support interoperability between distributed agents.

Such interactions may be particularly relevant for the coordination of networked monitoring nodes. For example, an agent operating at a monitoring station may detect an anomalous emission and notify other agents within the network. Coordinating agents may then trigger additional measurements from geographically distributed stations, correlate observations, or allocate tasks dynamically to improve emitter localization, classification or verification against license databases. This cooperative behaviour can improve responsiveness to dynamic spectrum conditions while optimizing the use of network and processing resources. The combination of MCP-like mechanisms and A2A interactions supports modular and scalable architectures where individual agents operate with controlled access to data and tools while contributing to broader system-level objectives.

The adoption of structured context protocols should be evaluated in accordance with national data governance policies, cybersecurity frameworks, and operational maturity. Such protocols can significantly enhance the transparency, explainability, and operational usefulness of AI-augmented spectrum monitoring systems.

4.6.3.5 Use Case: Radio monitoring coverage prediction system based on LLM

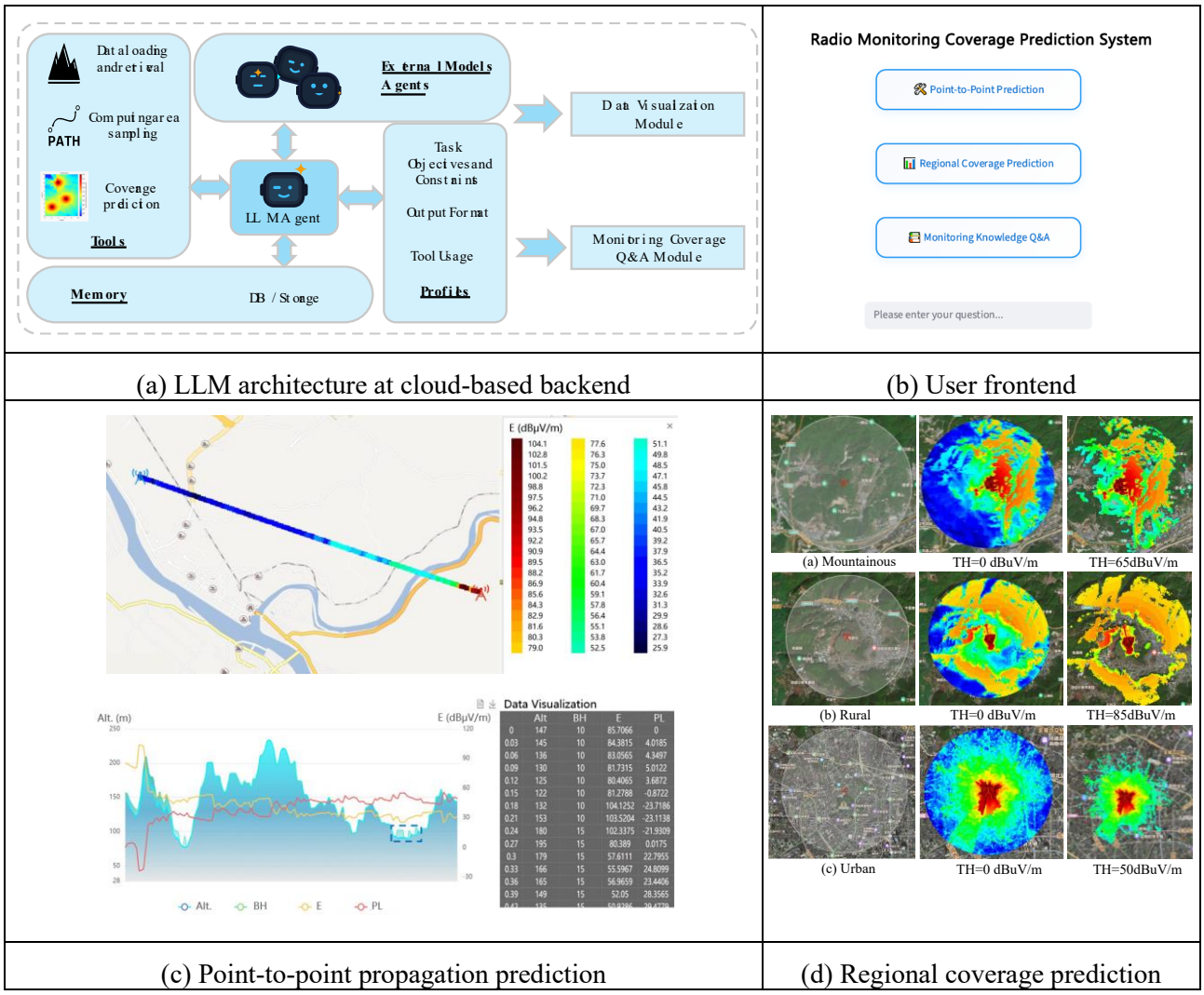
Some administrations are experimenting with Retrieval-Augmented Generation within the spectrum monitoring services. The integration of an LLM agent with information collected by radio monitoring stations (e.g. coverage measurements and propagation models) enables radio monitoring coverage prediction and data analysis through natural language interaction. The system supports point-to-point propagation prediction, regional coverage prediction, and Retrieval-Augmented Generation-based question answering for radio monitoring knowledge. It also provides a visual representation of spectrum utilization.

As shown in Fig. 4-30, the system is accessible through an HTTP front-end that interfaces with a cloud-based backend. Through this interface, users can access point-to-point propagation prediction results computed using models such as defined in the Recommendation ITU-R P.1812 that present the received field strength (E) and path loss (PL) along a transmit path. Key parameters such as altitude (Alt) and building height (BH) are also provided. This web interface also enables users to compare the predicted received field strength across three terrain types: (a) mountainous, (b) rural, and (c) urban areas. Coverage analysis is conducted using two threshold values (TH) with frequency and monitoring conditions held constant. These results illustrate that topographical and environmental factors profoundly impact the received spectrum.

This a simple example and does not represent a standard for minimum operational requirements; it should be adjusted to any other specific use case scenarios.

FIGURE 4-30

Spectrum monitoring and management system with LLM agent integration



(a) LLM architecture at cloud-based backend | (b) User frontend

(c) Point-to-point propagation prediction | (d) Regional coverage prediction

4.6.4 Human–AI collaboration and future directions

As discussed in this section, AI automation is increasingly being used to support data lifecycle tasks, from acquisition and pre-processing to analysis, reporting and archival. Automated systems can prioritise events, surface anomalies, and pre-fill reports.

To enable effective collaboration, automated systems rely on:

– transparent workflows that show intermediate evidence and explain the actions performed;

– configurable decision criteria and escalation paths to ensure fidelity of the decision process and system objectives; and

– records of automated actions for data security, auditability and accountability.

In this scenario, operator roles shift toward supervision, validation and investigation rather than repetitive measurement. Skill profiles tend to include:

– data literacy and familiarity with AI-assisted tooling;

– understanding of model limitations, bias and drift; and

– integration know-how across databases, archives and operational systems.

Training and organisational processes need to adapt accordingly, with emphasis on explainability, accountability and review of AI-assisted outcomes. This evolution raises organizational challenges including adapting workforce skills, maintaining transparency in automated processes, and ensuring accountability in regulatory decisions supported by AI-generated outputs.

Taking a step back to a broader view of the implications of AI developments, the potential benefits of advanced AI integration should be balanced with safeguards that ensure transparency and compliance with legal and ethical frameworks.

Administrations should be aware of the impact of these technologies across all action fronts, from observing the availability of APIs in current investments related to spectrum monitoring equipment and infrastructure, to redefining the roles of operators, ensuring adequate training, and adapting workflows to integrate AI tools.

It is essential to maintain human oversight, including safeguards against misuse and bias management by observing ethical aspects including privacy and personal-data protection with mechanisms for contestability and redress. Final responsibility remains with humans and thus, critical decisions and actions should not be fully automated but rather, rely on human-in-the-loop interactions.

To address these issues, some countries and regional administrations have established frameworks that may aid the adoption of AI tools within the spectrum monitoring services. Several examples of local regulations are promptly available online but there is no consensus on guidelines or recommendations in the broader international level.

Since 2024, ITU has organized summits (https://aiforgood.itu.int/) in partnership with the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) to engage key stakeholders and drive global collaboration in the development of AI Standards aiming to balance the drive for innovation by business and entrepreneurs with the risk management and accountability required by society in general.

Focusing on the spectrum monitoring domain, greater effort is needed to ensure that systems and processes can evolve considering the availability of fully functional APIs for data management and automation thus reducing the risk of early obsolescence while enabling a growing space for innovation in this area.

4.7 References

ITU Recommendations and Reports

Recommendation ITU-R SM.1370 – *Design guidelines for developing automated spectrum management systems*

Recommendation ITU-R SM.1393 – *Common formats for the exchange of information between monitoring stations*

Recommendation ITU-R SM.1394 – *Common format for Memorandum of Understanding between the agreeing countries regarding cooperation in spectrum monitoring matters*

Recommendation ITU-R SM.1537 – *Automation and integration of spectrum monitoring systems with automated spectrum management*

Recommendation ITU-R SM.1809 – *Standard data exchange format for frequency band registrations and measurements at monitoring stations*

Recommendation ITU-R SM.2117 – *Data format definition for exchanging stored I/Q data for the purpose of spectrum monitoring*

Report ITU-R SM.2542 – *Next generation spectrum monitoring – proactive, autonomous and data-driven*

Recommendation ITU-T X.1601 – *Security framework for cloud computing*

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CHAPTER 5

Measurements

TABLE OF CONTENTS

Page

Introduction 234
5.1 Practical considerations on measurements 234
5.1.1 Basic concept of measurement 234
5.1.2 Measurement environment 236
5.1.3 RF measurement domains 238
5.1.4 Measurement uncertainty 242
5.2 Measurement of frequency 242
5.2.1 General considerations 242
5.2.2 Common frequency measurement methods applied at stations for international monitoring 245
5.2.3 Crystal-controlled stage of frequency measurement equipment against a standard frequency 252
Bibliography 253
5.3 Measurement of RF level 253
5.3.1 Introduction 253
5.3.2 Measurement detectors 254
5.3.3 Level definitions 254
5.3.4 Influence of modulation 256
5.3.5 Necessary measurement bandwidth 256
5.3.6 Measurement procedure with a measurement receiver 258
5.3.7 Measurement procedure with swept spectrum analyser 258
5.3.8 Measurement with an FFT analyser 259
5.3.9 Correction for wide band signals 260
5.3.10 Channel power and adjacent channel power measurement 261
5.3.11 Typical problems encountered 264
5.3.12 Calibration of measurement equipment 268
5.3.13 Measurement errors 268
Bibliography 269
5.4 Measurement of field strength and pfd 269
5.4.1 General considerations 269

5.4.2 Choice of measurement sites 274
5.4.3 Methods of measurement 276
5.4.4 Evaluation, processing and documentation of measurement results 283
5.4.5 Calibration of measuring instruments and antennas 285
5.4.6 Field strength measurement for e.i.r.p. determination in the VHF and UHF bands 288
Bibliography 294
5.5 Bandwidth measurement 296
5.5.1 Bandwidth definitions 296
5.5.2 Bandwidth determination at monitoring stations 297
References 303
5.6 Modulation measurement 303
5.6.1 Introduction 303
5.6.2 Suitable measurement instruments 303
5.6.3 Analogue modulation 304
5.6.4 Single carrier digital modulation 306
5.6.5 Multicarrier digital modulation 313
5.6.6 Measurement errors 315
Bibliography 316
5.7 Radio direction-finding and transmitter localization 317
5.7.1 General considerations 317
5.7.2 Radio direction-finding 317
5.7.3 Location 335
References 364
5.8 Signal analysis and transmitter identification 366
5.8.1 Introduction 366
5.8.2 Capabilities needed to perform signal analysis 367
5.8.3 The process of signal analysis 368
5.8.4 Signal dynamics and analysis in the time domain 375
5.8.5 Advanced tools for signal parameter extraction 377
5.8.6 Correlation techniques 380
5.8.7 Traditional signal identification methods 382
Bibliography 390
5.9 Pulse measurements 390
5.9.1 Introduction 390
5.9.2 Basic pulse parameters 391
5.9.3 Measurements in the time domain 393
5.9.4 Measurements in the frequency domain 394

5.9.5 Special pulse characteristics 395

5.9.6 Equipment requirements 396

5.10 Spectrum occupancy measurements and evaluation 398

5.10.1 The term spectrum occupancy 398

5.10.2 Measurement considerations and evaluation options 399

5.10.3 Suitable receivers 400

5.10.4 Site considerations 401

5.10.5 Basic principles and measurement parameters 401

5.10.6 Notes on frequency ranges 407

5.10.7 Storage, presentation and analysis of collected data 407

5.10.8 Exchange of data 407

5.10.9 Examples 408

Bibliography 410

5.11 Coverage measurements 411

5.11.1 Introduction 411

5.11.2 Ways of taking measurements 412

5.11.3 Basic considerations 412

Bibliography 417

5.12 Unwanted emission measurements 418

5.12.1 Introduction 418

5.12.2 Definitions and terminology 418

5.12.3 Frequency ranges of unwanted emissions 419

5.12.4 Measurements in the spurious domain 420

5.12.5 Measurements in the out-of-band domain 420

5.12.6 Equipment requirements, setup and measurement limitations 423

5.12.7 Optimizing the dynamic range of the measurement setup 423

5.12.8 Required equipment 424

5.12.9 Practical aspects of the measurement 424

Bibliography 427

Introduction

This Chapter discusses the elementary set of measurement operations for any radio spectrum monitoring service. The topics, procedures and practices found here do not deal with specific types of emission or radio service as they reflect the key concepts, quantities and procedures common in radio spectrum monitoring. Not any technique is suited for any kind of signal or frequency range. More special matters tailored specifically to a certain field of work beyond the more common equipment – e.g. quantities and methods for satellite monitoring or matters related to non-ionised radiation (E.M.F.) can be found in Chapter 6. More details on issues like FFT, the use of GNSS for spectrum monitoring purposes and analyses of measurement uncertainties can be found in Chapter 7. The measurement instruments discussed in Chapter 3 will be used extensively throughout this Chapter.

Chapter 5 – Measurements – contains material related to:

5.1 – Practical considerations on measurements: what is a measurement, common locations and domains in spectrum monitoring;

5.2 – Measurement of frequency;

5.3 – Measurement of RF level: focused on what is happening inside spectrum analysers and monitoring receivers, different ways of setting up level measurements;

5.4 – Measurement of field strength and power flux-density: relating levels on the instrument to the quantities on air;

5.5 – Bandwidth measurement: what do they mean and how to make them;

5.6 – Modulation measurement: basic means to describe how a signal carries information;

5.7 – Radio direction-finding and transmitter localization: tracking the source of a radiation;

5.8 – Signal analysis and transmitter identification: methods of extracting detailed descriptions of a signal;

5.9 – Pulse measurement: basic measurement techniques to describe pulsed signals;

5.10 – Spectrum occupancy measurements and evaluation: what are occupancy measurements and how to interpret the results;

5.11 – Coverage measurements: what is coverage and what are the key tools and concepts for such measurements;

5.12 – Unwanted emission measurement: what are those emissions and what approaches exist to measure them.

5.1 Practical considerations on measurements

5.1.1 Basic concept of measurement

Measurement is the process of quantifying an attribute or phenomenon for the purpose of comparison to a reference. The result is, in principle, independent of the procedure used. Nevertheless, using a proper measurement process is essential to obtain an accurate and repeatable result (as far as the signal scenario is repeatable at all).

The measurement process should define:

– Attribute or phenomenon to be measured.

– Conditions of measurement operations.

– The measurement system and parameters to use.

– Measurement procedure to be used.

– Analysis of the result and associated uncertainties.

5.1.1.1 Attribute or phenomenon to measure

In spectrum monitoring, the electromagnetic fields being measured could be described as either E- or H-fields or as the characteristics of a signal (frequency, amplitude, duration, phase, bandwidth, etc.).

Moreover, from these basic measurements, a more complex measurement process may be implemented to characterise the quality and performance of a system or an emitter such as spectrum occupancy and coverage measurements. In this case, the result is a combination of several measurements like time, frequency, amplitude, etc.

5.1.1.2 Conditions of the measurement operations

Conditions of the measurement operation should be considered because of the direct influence on the procedure and the outcome. Measurement results are to some degree dependent on the environment, so details of the conditions have to be known to ensure the measurement is reproducible.

The advantage of laboratory conditions (conducted measurement or radiated measurement in an anechoic chamber) is that the environmental influences are well known and can be compensated for. Additionally, measurements are highly repeatable so meaningful comparisons between devices or systems can be made with a high degree of confidence.

However, most of the measurements performed by spectrum monitoring departments are made in the field with many influences from caused by surrounding infrastructure, buildings and weather. Limitations of the measuring equipment must also be taken into consideration:

– type of monitoring station (e.g. fixed, mobile, portable);

– size, weight, and power requirements of portable equipment;

– size of antenna elements;

– access to test points or measurement sites.

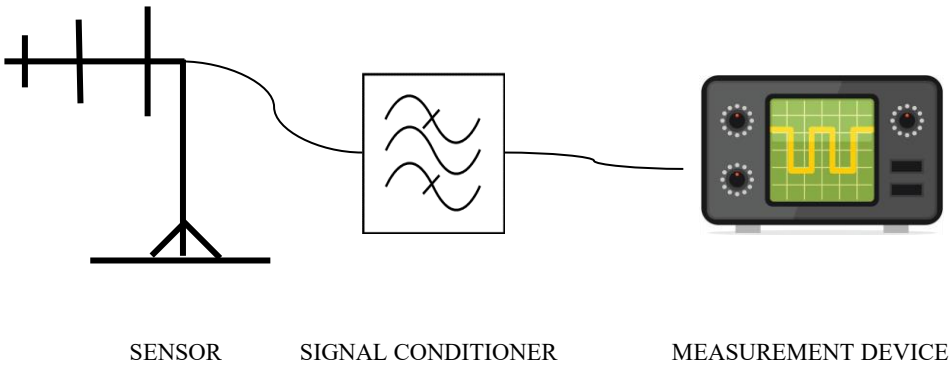
All necessary precautions should be taken to limit outside influences and conditions of operations should be specified in the measurement process to ensure repeatable measurements.

5.1.1.3 Measurement system

A measurement system comprises all equipment, accessories, computer and software packages used to make a measurement. It can be divided into three parts:

FIGURE 5-1

Basic measurement system



The sensor is the device which converts the electric or magnetic field into an electrical signal. In terms of spectrum monitoring, the sensor is usually a probe or an antenna.

The signal conditioner is used to isolate and optimize the signal(s) from the sensor for a better measurement considering the conditions present during the operation. Examples are: filters, amplifiers, attenuators, couplers, mixers.

The measuring equipment is the device which receives the signal, extracts its parameters, displays and / or records it for further exploitation. Typical examples are spectrum analysers or monitoring receivers.

The measurement process should always take into account the specific parameter(s) to be measured and specify the type of equipment and settings accordingly.

5.1.1.4 Measurement procedure

A general description of how to perform the measurements is provided below:

– Develop a plan for the measurement that includes the site and duration of the measurement campaign. A list of the measurement results should be put into a table to be completed at the site during the measurement process. For example, the task may be to record the field strength of a service at specific times, frequencies, and locations.

– Depending on the location, preliminary measurements or research may be required to ensure a suitable measurement environment (e.g. checking for a strong emitter near the measurement site which could impact the result). Good planning reduces the time in the field required to perform the measurements.

– Look up the required measuring equipment specifications of the service being measured to make sure the frequency range, instantaneous bandwidth (IBW), resolution bandwidth (RBW), sensitivity and amplitude accuracy are sufficient.

– Develop a list of sensors, signal conditioning, cables, adapters, and measuring equipment based on the plan. If the measurement location is unfamiliar, a wide range of signal conditioning components may be needed to adapt to different operating conditions. All measurement equipment and accessories should have a current calibration certification.

– Execute the measurement plan as defined and record the results accordingly. It is good practice to pause after the initial results are obtained and check them against theoretical estimates or measurements on the same service from the same location at a previous date. When there is confidence that the measurements are being performed in an accurate and repeatable manner consistent with other results, continue as planned.

5.1.1.5 Analysis of the results and measurement uncertainties

Post-processing and analysis of the results is necessary to account for the uncertainties in the entire measurement chain to assess the uncertainty of the final results. Publication of the report should include a list of the personnel, locations, times, measuring equipment, and the uncertainties associated with each set of measurements.

Section 7.9 provides details on the measurement uncertainty.

If necessary, the final step would be to specify the form of publication of the results.

5.1.2 Measurement environment

The measurement environment describes the conditions present during the operation that may impact the results (in terms of accuracy and repeatability). Examples include reflections from buildings (multipath), moving reflectors such as cars and public transportation, the ambient signal environment including strong emitters at or near the frequency to be measured. The measurement environment may also affect the equipment requirements and schedule of the operation.

– Urban settings typically have high multipath, strong nearby emitters, and a complex RF background with noise from construction equipment and vehicles.

– Rural settings are usually very different with wide open spaces, few/no nearby strong emitters and less RF background activity.

– Laboratory settings are controlled, and their RF characteristics are understood making a suitable environment for accurate and repeatable measurements.

For example, to validate the technical specifications of radio equipment, some measurements are best performed in an anechoic chamber. Conversely, to solve interference cases measurements must be performed

on site. It is important for the monitoring service to be capable of performing measurement operations in different environments.

5.1.2.1 Laboratory environment

Although a laboratory is not required to perform most spectrum regulatory tasks, an increasing number of activities require such means.

The main advantage of a laboratory environment, as opposed to a real environment, is that the environment is well known. In many cases, this can simplify the measurement requirements and reduce associated uncertainties.

When tests require a controlled electromagnetic environment not disturbed by external radiations, two methods may be considered:

– conducted measurement when a test point is available;

– radiated measurement in a controlled environment.

Conducted measurements are performed mainly to test the signal from a source at the output (just before the antenna) and must be accommodated by a suitable test port.

However, more systems have advanced antenna systems integrated within the transmitter and may not have a test point at all. In this case, analysis of the device's radiated signal cannot be done in a conducted manner.

For radiated measurements, a controlled electromagnetic environment is achieved by means of a shielded room or enclosure that attenuates external signal energy to the point that it has negligible effect on the measurement. Some tests require elimination of multi-path effects and in this case, an anechoic chamber (or enclosure) should be used.

Measurement operations that should be performed under such conditions include:

– compatibility measurements between systems (e.g. a preliminary study of new systems which shall share the same frequency band or use an adjacent frequency range);

– checking technical specifications of measurement equipment (e.g. antenna gain);

– compliance of radiated emission of a device before commercialising (e.g. out-of-band emissions, spurious emissions).

Nevertheless, most monitoring measurements are performed in the field (in situ) in real electromagnetic environments.

5.1.2.2 In situ measurement

The primary tasks of a spectrum monitoring service are to check the emission compliance (compared to declarations), to identify interference sources and to perform coverage or QoS measurements. Such measurements must be done in the field.

These tasks are accomplished by means of fixed stations, mobile stations and mobile measuring equipment. Depending on the operating conditions, the main advantage of a mobile station is flexibility regarding to the choice of the measurement site. However, the advantage of a fixed monitoring station is the knowledge of the spectral environment at measuring site. Having a strong knowledge of the baseline spectral activity (e.g. occupancy reports) makes it easier to detect new signals or compare to the emitter database.

Even though the environment is not under control, some precautions can be to limit RF interactions with the signal of interest and obtain an accurate result. Some common precautions to consider are:

– Ensure the measurement site to be in far-field from the emitter when required;

– Ensure a sufficient decoupling height of the measurement antenna to avoid influence of the soil;

– Choose a measurement site with minimal obstacles (building, constructions, trees, etc.) to reduce the impact of reflections, signal attenuation and other multi path effects;

– Choose a measurement antenna matched to the desired frequency range and check if the antenna's polarization plane matches to the incident signal;

– Avoid measurement sites with strong electromagnetic fields in close vicinity, if possible.

5.1.3 RF measurement domains

The signals received in a monitoring station may be characterised using the time, the frequency or the phase domain by using instruments like spectrum analysers, monitoring receivers or vector signal analysers.

These three ways of analysing a signal provide the advantage of changing the perspective of the signal's behaviour. By leaving the perspective of the frequency domain, the ability to understand signal dynamics can become quite clear in the time or phase domains. After developing the concepts of each domain, the types of measurements are introduced. The merits of each generic measurement type are discussed to give the reader an appreciation of the advantages and disadvantages of each approach.

Apart from those signal domains directly accessible on a measurement instrument, more indicators exist to describe the peculiarities of a signal, like the received position, antenna orientation and polarization, absolute time of reception of the signal and weather conditions.

5.1.3.1 Time and frequency domains

Figures 5-2 and 5-3 show examples of periodic and aperiodic signals in time and frequency domains.

The frequency domain representation is especially well suited to observe channel occupancy, interference, harmonic products and spurious emission. Further, the characteristic spectrum displays of the different modulation modes can assist in identifying the modulation type and symbol rate of the signal of interest. The time domain representation reveals the time dependence of signal amplitudes and the time required (e.g. for the peak detector) for the correct measurement of the signal amplitude. Especially when investigating emissions from digital systems, the time domain helps to measure parameters of time-division multiplex such as burst and idle time, number of time slots occupied and power ramping.

FIGURE 5-2

Some periodic signals in the time and frequency domains

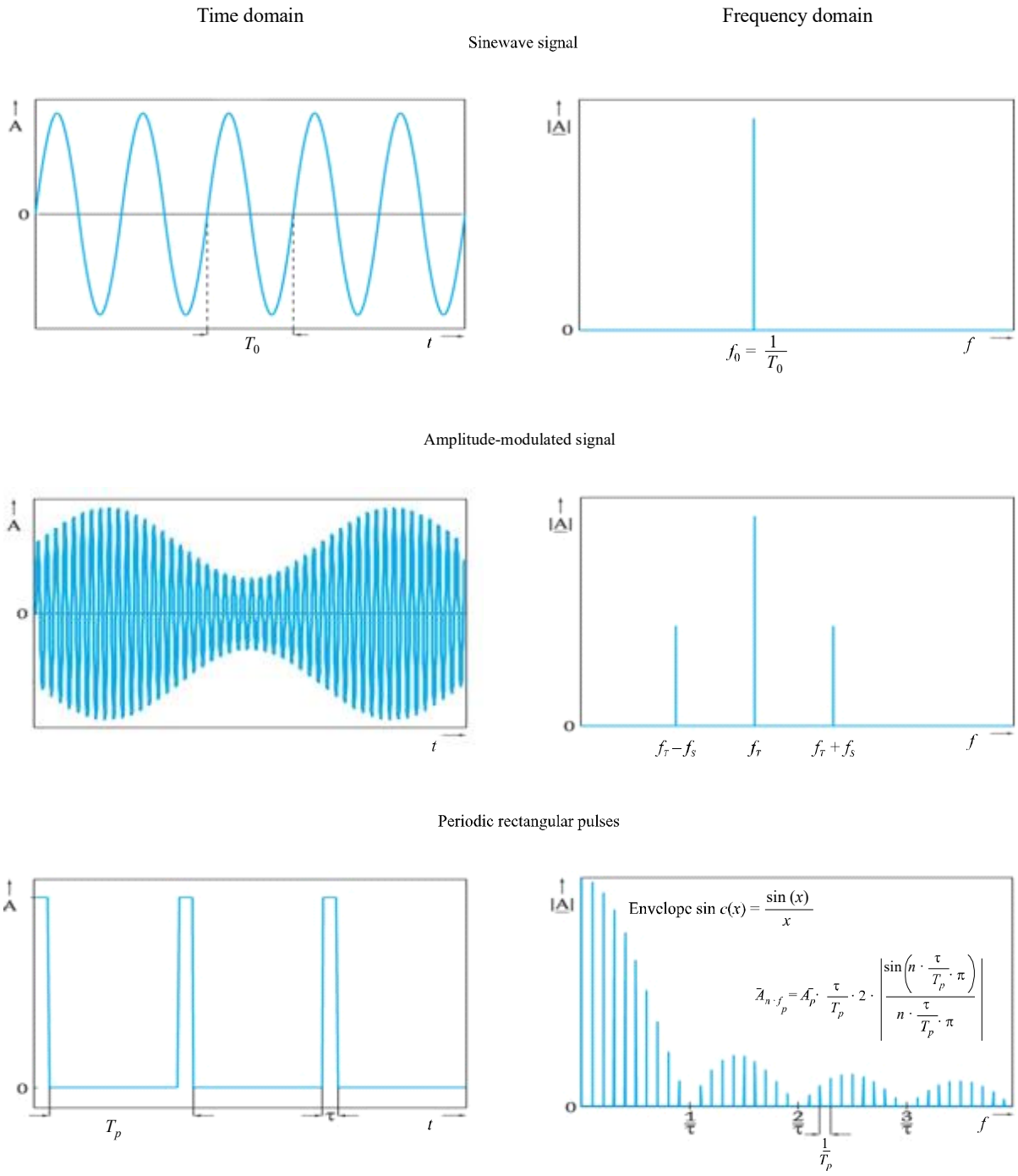


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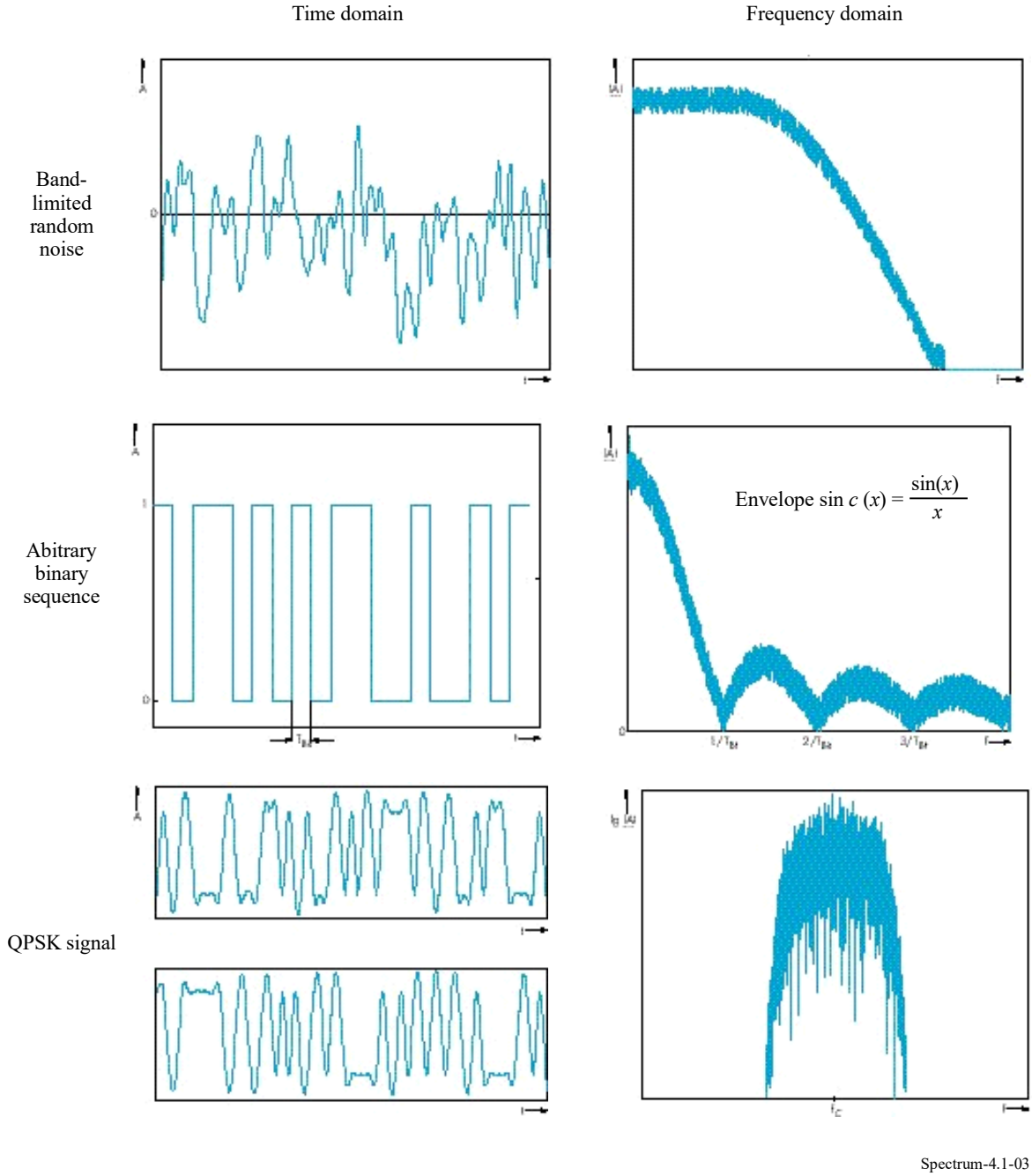
FIGURE 5-3

Some aperiodic signals in the time and frequency domains

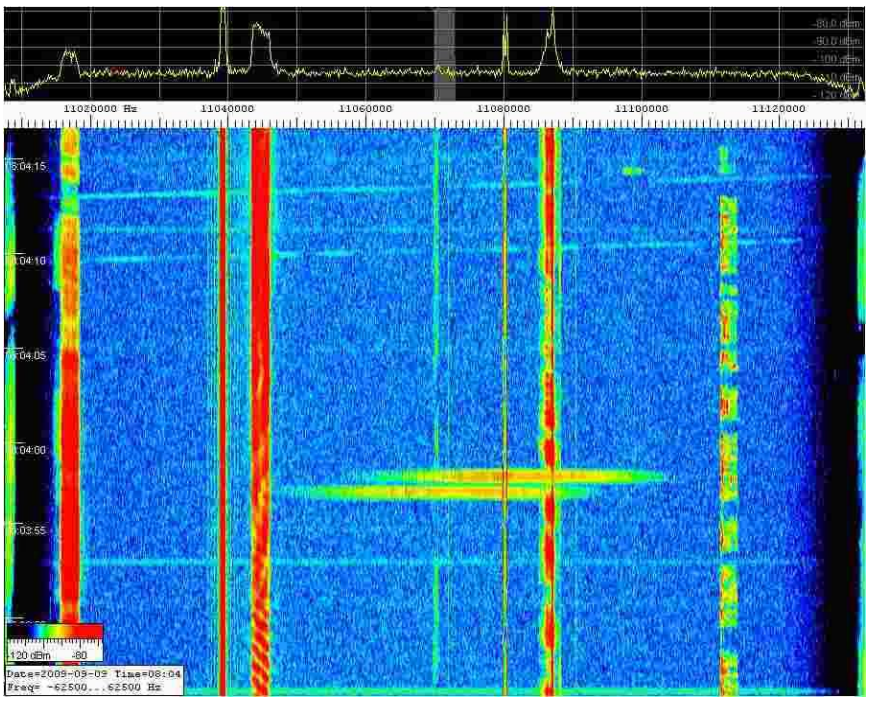


The time domain may be suitable to detect and to analyse short duration burst signals or transient effects which are not detectable with a traditional spectrum analyser.

The discussion above covers amplitude versus time and amplitude versus frequency. Another useful display for the monitoring service spectrogram which depicts both frequency and amplitude versus time (see Fig. 5-4) to observe, for example, the frequency spectrum occupation. This representation displays values of amplitude with the colour scale. Such representations are useful to capture broadband emissions or to track an emission with a frequency drift or a frequency hopping pattern.

FIGURE 5-4

Example of a spectrogram



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5.1.3.2 Amplitude and phase domains (vector analysis)

Most digital radiocommunication systems modulate the phase of the RF carrier (PSK, QPSK etc), or phase and amplitude together (QAM). The frequency domain, however, is not able to display phase information. To observe that, the emission is usually displayed in a constellation diagram by a vector signal analyser or software package, see Fig. 5-5. The vector length from the origin to each of the points of the constellation diagram represents the signal amplitude whereas the angle between the positive x-axis and the vector, measured counter-clockwise, represents the phase. The in-phase component ("I") of the signal is represented on the x-axis (real part) and the quadrature component ("Q") on the Y-axis (imaginary part).

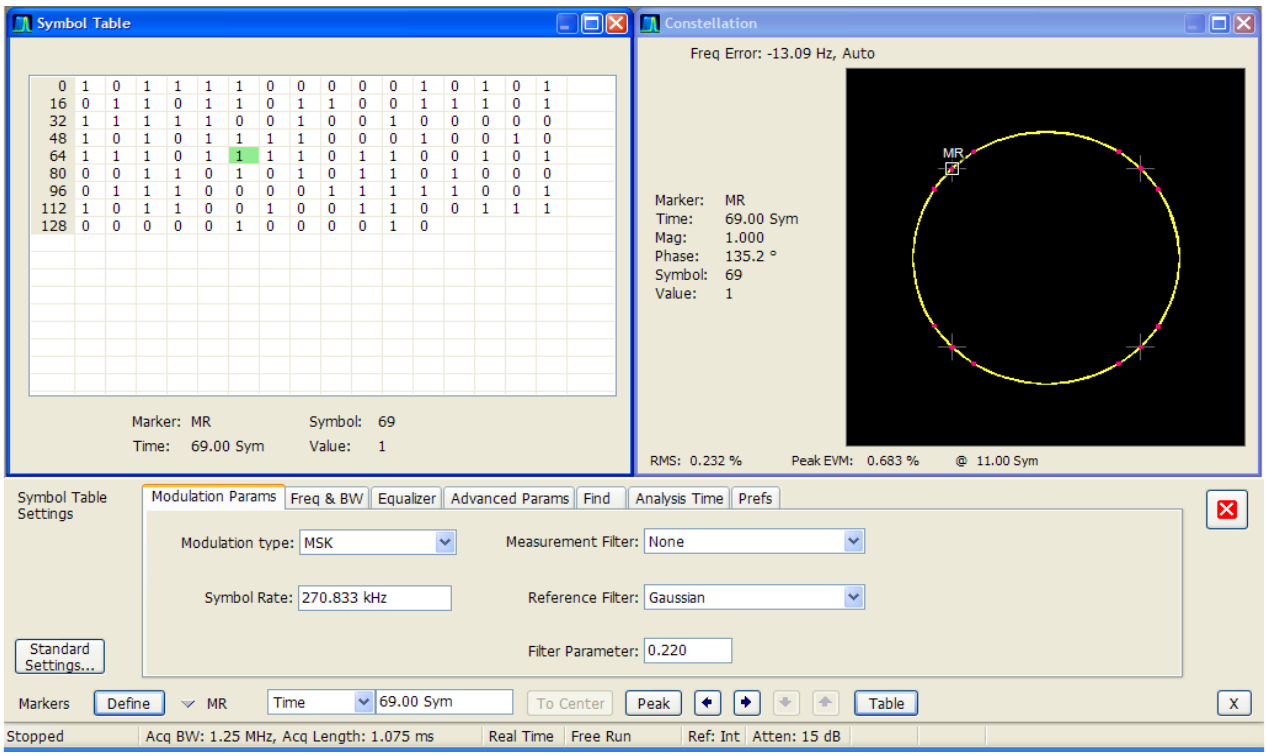
The repetition frequency of this display must be equal to the symbol rate transmitted. To achieve a stable presentation of the constellation, the analyser has to synchronize with the signal. To facilitate this, the modulation scheme or at least the symbol rate must be known.

In simple cases, when the modulation mode and the encoding scheme are known, the analysis can be done in real time. Modern vector signal analysers are then able to display the binary signal sequence, or characters of the decoded information.

However, in the case of a more sophisticated modulation scheme and in cases where either the modulation scheme, symbol rate or the encoding is unknown at receiving time, subsequent processing is necessary to get the transmitted code.

FIGURE 5-5

MSK signal as constellation diagram (amplitude-phase domain)



5.1.3.3 FFT analysis

The Fast Fourier Transform (FFT) is an algorithm for transforming data from the time domain to the frequency domain. It is the basis for many modern signal analysis software packages, spectrum analysers 0and monitoring receivers. FFT-based products often enable analysis of a signal in each of the domains described above (time, frequency, amplitude and phase). The FFT technique is described in more detail in § 7.7.

5.1.4 Measurement uncertainty

A complete measurement result should include a statement regarding the results uncertainty. It should be considered by the monitoring service when determining compliance or non-compliance with a regulatory limit. Regulatory measurements include the measurement of frequency, signal levels, and occupied bandwidth. In these cases, regulatory limits define maximum values of frequency offset, effective radiated power (e.r.p.) and occupied bandwidth.

For more details, see § 7.9 on uncertainties calculations.

5.2 Measurement of frequency

5.2.1 General considerations

Determination of the correct frequency of an emission is the most fundamental measurement required for proper management of the radio spectrum. Accurate frequency measurements can be made using a variety of different methods and equipment. In all cases, the accuracy depends on the frequency standard. Frequency standards derived from GNSS signals are available in many modern spectrum analysers and monitoring receivers and provide highly accurate frequency references. The other important element of the measuring equipment is the frequency resolution which can limit accuracy. GNSS locked frequency standards and rubidium standards achieve high levels of accuracy that can now be achieved without undue cost in both fixed and mobile monitoring stations. Use of a GNSS frequency standard also solves the problem of traceability of measurements and frequent accuracy checks of receiver synthesizer accuracy, if the measurement environment allows the use of those systems. Guidance on the requirements for frequency accuracy are found in Recommendation ITU-R SM-377.

In this section, the term frequency "standard" refers to a source derived from a universally accepted frequency such as GNSS or an atomic clock. Frequency "reference" is what a measuring device uses as the basis for its local oscillators. A frequency reference may be internal or external to the measuring equipment.

Frequency measurements at monitoring stations are performed with receivers or spectrum analysers. Occasionally, other devices like simple frequency counters might suffice. For a detailed description of available device types and the technical requirements, refer to Chapter 3.

In order to obtain results that cannot be contested, the receivers should have the following properties:

– high input sensitivity;
– satisfactory image-frequency rejection;
– low cross-modulation and intermodulation;
– proper input filters (preselector) to protect the frequency band used for measurement against unwanted frequencies;
– an external frequency standard input;
– low phase noise of the internal oscillators;
– either manual or remote controlled or automatic gain control;
– transparent IF output for additional measurements.

Internal carrier(s) used at mixer(s) in the receiver must be derived from a frequency standard.

External or internal signal generators for frequency measurement should have the following features:

– the frequency must be synthesized from a frequency standard;
– the internal frequency standard should have an error of less than 10^{-7} for the frequency itself and all frequency steps;
– the smallest step should be 1 Hz or less;
– there should be an external frequency standard input for 1, 5 or 10 MHz;
– stand by operation of the internal frequency standard should be possible;
– the frequency range should cover the range of frequencies to be measured;
– harmonics should be attenuated by at least 30 dB;
– non-harmonics should be attenuated by at least 80 dB;
– low phase noise (less than −100 dBc/Hz at 10 kHz offset from the carrier);
– output voltage should be variable from 1 mV to 1 V across 50 Ω.

Important considerations when planning frequency measurements include:

– the accuracy and stability of the measuring equipment frequency reference;
– measurement procedure;
– resolution of result readout (number of digits);
– available measurement time of the signal of interest in terms of:
  - frequency stability;
  - amplitude dynamics.

The measuring procedures described below are manual methods. Even though they have been partly superseded by automated methods, they are still of importance:

– for simple and low-cost measuring installations;
– for the training of monitoring operators;
– for a monitoring service at the beginning of its operation;
– in cases where automated systems fail, e.g. due to weak signal or interference conditions.

As pointed out in § 5.1.1, frequency measurement usually means a comparison between an unknown frequency and a known frequency (reference frequency). Based on this comparative process, the following frequency

measurement methods are applied at monitoring stations (some ad-hoc abbreviations are used for easy reference in Table 5-1 only):

– FFT method,
– Swept spectrum analyser (SSA) method,
– Instantaneous frequency measurement (IFM) method,
– Beat frequency (BF) method,
– Offset frequency (OF) method,
– Direct Lissajous (DL) method,
– Frequency counter (FC) method,
– Frequency discriminator (FD) method,
– Phase recording (PR) method.

Table 5-1 shows the appropriate applicable frequency measurement methods as a function of the type of emissions. It should be noted that the FFT and SSA methods apply to virtually all types of emissions and for that reason are most commonly used.

TABLE 5-1

Examples of frequency measurement methods

	BF	**OF**	**DL**	**FC**	**FD**	**PR**	**SSA**	**IFM**	**FFT**
Continuous carrier (N0N)	X	X	X	X	X	X	X	X	X
Morse telegraphy (A1x)	X	X	X		X		X	X	X
Morse telegraphy (A2x; H2x)	X	X	X	X	X	X	X	X	X
Radiotelegraphy (F1B; F7B)	X	X	X		X		X	X	X
Facsimile (F1C)	X	X	X		X		X	X	X
Broadcasting and radiotelephony (A3E)	X	X	X	X	X	X	X	X	X
Broadcasting and radiotelephony (H3E; R3E; B3E)	X	X	X		X	X	X	X	X
Broadcasting and radiotelephony (F3E)				X	X		X	X	X
Radiotelephony (J3E)							X		X
OFDM, digital broadcasting (X7WXX)							X		X
Analogue television broadcasting (C3F)	X	X	X	X	X	X	X	X	X
FDM Radio relay (F8E)				X			X	X	X
Pulsed radar signals					X		X	X	X
Cordless telephone systems (F1D, F2x, F3E, G3E)							X	X	X
Point-Multipoint TDMA systems							X	X	X
Cellular telephone systems (IMT)							X	X	X

The method of determining the accuracy of frequency measurements should meet the following conditions:

– Measurements should be made under optimum reception conditions, to prevent introduction of impairments such as fading or interference that may impact the measurement result. The use of portable or mobile measuring equipment can often mitigate these influences because of better access to the emitter and fewer environmental effects.
– The measurement report should include a description of the method's total error. This includes the errors due to the measuring equipment but excludes the frequency standard's error contribution).
– As the error will probably be different for different classes of emission, the error has to be determined for each class.

– As the error will vary from one measurement to another for a particular class of emission and as the errors cannot be less than the measurement equipment's resolution, the results may be treated statistically.

– When the accuracy of the measurement system is described (frequency standard as well as measuring equipment and method), the error should be given for each of the contributing factors. As shown in equation (5-1), the maximum error of the whole system is given by the sum of the absolute values of the errors due to the frequency standard and the method of measurement.

Like every other measurement, frequency measurements are subject to errors. The following must be considered:

– errors due to the method of measurement ($\Delta f_M/f$);

– errors due to the modulation of the signal to be measured ($\Delta f_{mod}/f$);

– errors of the reference frequency ($\Delta f_R/f$);

– errors due to the technical characteristics of the measurement arrangement including the reading inaccuracy and resolution ($\Delta f_A/f$);

– errors on the transmission path (see below) ($\Delta f_T/f$).

The maximum relative error $\Delta f/f$ can be estimated from the sum of the individual errors:

$$\Delta f/f = \pm(|\Delta f_T/f| + |\Delta f_R/f| + |\Delta f_M/f| + |\Delta f_A/f| + |\Delta f_{mod}/f|) \quad (5\text{-}1)$$

In band 7 (HF), and to a smaller extent even in bands 6 (MF), 5 (LF) and 4 (VLF), the accuracy of frequency measurements is not only limited by the method of measurement and the type of modulation of the transmitter, but also by frequency variations introduced by the transmission path. When making tests in band 7 (HF), departures up to ±3 parts in 10^{12} between the incoming and the radiated frequencies have been experienced at night on a transmission path of more than 1 000 km. There is also a mean diurnal variation of the frequencies. The smallest differences are to be expected when both the transmitter and the receiver are in the daylight zone. In this case the frequency departures are mostly less than 3 parts in 10^8. Diurnal variations are also to be found with emissions in bands 5 and 4. Here the variations are typically on the order of 1 part in 10^9 provided the transmission distance does not exceed several hundred kilometres. However, in many cases these restrictions are of minor importance.

5.2.2 Common frequency measurement methods applied at stations for international monitoring

5.2.2.1 Direct Lissajous method

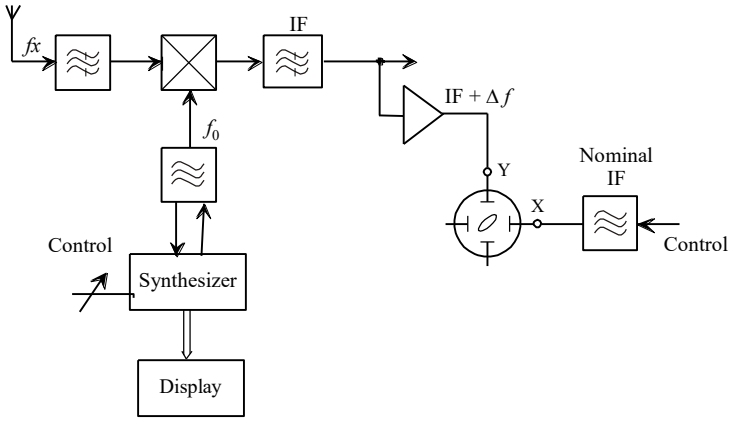
This measurement method makes use of an oscilloscope in X-Y mode to compare a receiver's IF output signal to a known reference frequency. The resulting pattern shown on the display is analysed. If an accurate and stable frequency synthesizer is used as the reference for the receiver, the displacement of the IF from the nominal value is equal to the displacement of the received frequency from the set frequency.

To make Direct Lissajous measurements, connect the receiver IF-output to the Y-amplifier/input and a frequency reference corresponding to the nominal value of the IF to the X-amplifier/input of the oscilloscope (see Fig. 5-6).

The resulting display forms a pattern on the screen, showing the relationship between the frequency and phase of the received and reference signal. If the two signals are perfectly aligned in frequency and phase, the oscilloscope will display a straight line at an angle of 45 degrees. A moving pattern indicates a frequency difference between the two signals. If the frequency synthesizer is provided with an interpolation scale, it is necessary to measure while the ellipse appears to be stationary.

FIGURE 5-6

Direct Lissajous method



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5.2.2.2 Frequency counter method

Frequency counters are different from other methods in that they use hardware circuits to directly measure the frequency of the signal and provide very accurate results. The most common application is the direct measurement of N0N signals – possibly that of a frequency reference or other unmodulated carrier. Counters can also be used to measure a signal at the IF from a spectrum analyser or monitoring receiver. Modern counters have analysis and statistical features enabling advanced measurements on some forms of analogue modulation. Histogram plots show the distribution of measured frequencies to view stability, jitter, Allen variance, or noise issues. Trend plots show drift over long periods of time.

There are two basic types of frequency counters: direct counting and reciprocal counting. Direct counters count the number of cycles of the signal (zero crossings) for a known period also known as the gate time. The result is displayed on the counter's readout. The direct counter's resolution is defined in Hertz. For example, if the gate time is set to 1 second, the lowest frequency the counter can detect is 1 Hz. With a 1-second gate time, when measuring a signal of 10 Hz, the best resolution is 1 Hz or two digits on the display.

A reciprocal counter measures the input signal period and then computes the reciprocal to display the frequency readout. The frequency resolution is fixed in the number of digits displayed for a given gate time. A reciprocal counter will always display a certain number of digits for a specific gate time (e.g. 10 digits per second).

If the best precision and speed are important to the measurement, a reciprocal counter is well suited. Universal counters also offer different frequency and time-related measurements such as:

– Frequency: the number of full cycles completed per unit time

– Period: the time interval of a full cycle of the signal

– Frequency ratio: measurement of the frequency ratio of two input signals

– Time interval: measurement of the time delay between events of two input signals

– Rise and fall times: the times taken by a digital signal to go from low to high states and back

– Phase angle: measurement of the phase difference between two input signals.

Apart from the intrinsic inaccuracy of the crystal standard, the accuracy of the frequency counter is restricted to a ±1 count of the last digit. To operate correctly, frequency counters also require a clean and sufficiently high input voltage during the whole period of measurement.

State-of-the-art receivers have oscillator frequencies which synthesized and derived from an internal frequency standard. Therefore, an input frequency, which is equal to the frequency setting of the receiver, will be converted to the nominal value of the intermediate frequency (IF). Hence the IF counter whose frequency indication is corrected by the oscillator frequency (or frequencies) used will indicate the input frequency.

In view of the integrating property of the frequency counter, this method is very suitable for the measurement of FM signals, as long as the gate time of the counter remains much greater than the period of the lowest modulation frequency.

5.2.2.3 Swept spectrum analyser method

The swept tuned spectrum analyser method is often used at monitoring stations for measuring frequencies of received signals. A synthesized oscillator, whose output frequency is derived from an internal or external frequency standard, is applied to tune a modern spectrum analyser. In all cases, the calibration of the analyser should be current and the RBW/VBW should be set to AUTO so they will reduce as the span is reduced.

When using a swept tuned analyser to measure frequency, the frequency span and RBW settings are important to assure an accurate measurement. The frequency span should be adjusted such that only the signal being measured is displayed; this effectively reduces errors associated with the span. The resolution and video bandwidth should be set as narrow as possible while maintaining a reasonable sweep time. The frequency accuracy of a swept tuned analyser has several dependencies – including the accuracy and stability of the reference, frequency span and resolution bandwidth.

The steps associated with this method of frequency measurement include:

– Tune the centre frequency of the analyser to match that of the signal being measured.

– Reduce (zoom) the frequency span down to the point that only the signal to be measured is displayed. This may involve resetting the centre frequency as the span is reduced. “Marker to peak” and “marker to centre” display features can expedite this process.

– Adjust the reference level of the analyser to move the peak of the signal to the top of the display.

– If the RBW and sweep time are coupled, the sweep time is compatible with the resolution bandwidth.

– User “marker to peak” to determine the peak of the signal and use the marker value as the frequency.

In the case of some digital modulations, unlike most analogue modulations, it is difficult to find a characteristic frequency in the spectrum of the emission (e.g. the carrier). However, in such cases, the centre frequency can be calculated from the upper and lower boundary of the occupied bandwidth (see Fig. 5-7). Most modern spectrum analysers, monitoring receivers and signal analysis software include the ability to display the occupied bandwidth (see § 5.5), centre frequency (based on centroid) and frequency offset.

The centre frequency by the centroid method is stated as:

$$f_c = (f_l + f_u)/2 \tag{5-2}$$

where:

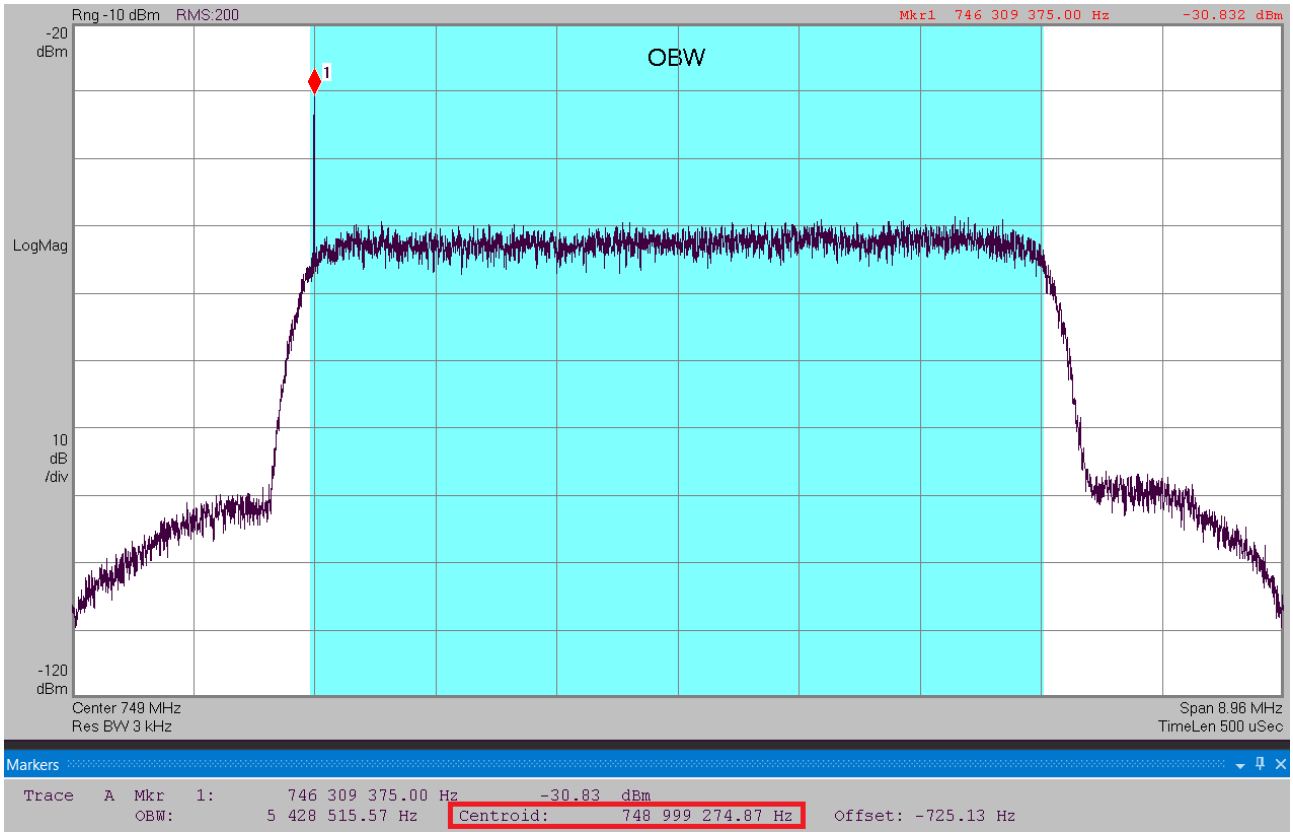
f_c: the centre frequency of the spectra

f_l: the lower frequency value of the occupied bandwidth

f_u: the upper frequency value of the occupied bandwidth.

FIGURE 5-7

Spectra of a HDTV broadcast signal with VSB8 modulation



5.2.2.4 Instantaneous frequency measurement method (IFM method)

The IFM method compares two versions of the signal of interest: the original and a delayed version to measure the phase difference from which the frequency can be derived. This method can be performed very fast and with high accuracy. This method can be useful when measuring the frequency of short duration or frequency agile signals.

By using digital measurement receivers equipped with digital signal processing and using techniques such as IFM, both the accuracy and speed performance can be guaranteed, while providing simultaneously several advantages: high fidelity/repeatability of measurements, averaging functions, filtering, automation of measurement.

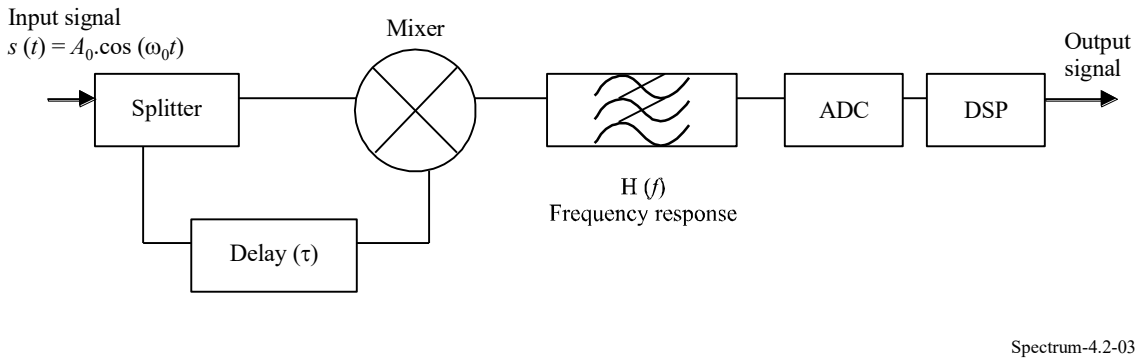
5.2.2.4.1 Principle

One principle of IFM techniques is an autocorrelation process of the captured signal. After filtering, the result of the operation is digitized and processed with a DSP to determine the exact frequency of the signal.

The basic principle could be illustrated with the following diagram:

FIGURE 5-8

Basic principle of IFM technique



The signal processing, in the time domain, consists in splitting the input signal in two signals.

Afterwards, the signal itself and the same signal delayed are mixed. This results in two terms:

$$s_{Mix,Out}(t) = \left(\frac{A_0}{2}\right)^2 [\cos(\omega_0\tau) + \cos(2\omega_0\tau - \omega_0 t\tau)] \quad (5\text{-}3)$$

The first term is proportional to the frequency and the delay applied to the signal, the second term is the second harmonic of the signal which is suppressed by the low-pass filter.

After digitizing, the instantaneous frequency f_0 can be estimated by the DSP according to the following relation:

$$f_0 = \frac{1}{2\pi\tau}\arccos\left(\frac{8s_{Mix,out}(t)}{A_0^2 H(f_0)}\right) \quad (5\text{-}4)$$

Another principle of the IFM could be described as an analysis of the phase of the signal.

The input signal is digitized, filtered and demodulated in I/Q.

The instantaneous phase φ of the signal is reckoned as arctan(Q/I) for each sample. The instantaneous frequency f_n is deducted from the following relation, with τ_s being the sample duration:

$$f_n = \frac{\varphi(n) - \varphi(n-1)}{2\pi\tau_s} \quad (5\text{-}5)$$

By averaging consecutive instantaneous frequencies, the central frequency of the input signal could be calculated.

5.2.2.4.2 Performance of IFM techniques

Typically, it is possible to obtain a measurement result every second or faster (200 ms) while maintaining an accuracy on the order of 1 Hz or better on unmodulated carriers or carriers of amplitude modulated signals.

These measurement times are compatible with signals the centre frequency of which drifts slowly, and also make it possible to evidence drift characteristics by consecutive measurements.

Digital signal processing techniques make it possible to perform measurements with very high accuracy and fidelity/repeatability at reasonable costs. Accuracy of the order of 10^{-10} on an unmodulated carrier can be reached easily provided the measuring equipment is referenced to a suitable frequency standard.

Therefore, the accuracy of frequency measurements in modern monitoring stations can reach about 1 Hz from 9 kHz up to the higher UHF frequencies (3 GHz) on unmodulated carriers. This performance is compatible and required if only to check one of the most stringent frequency accuracy needs described in ITU-R Recommendations, namely the frequency setting of analogue TV broadcast transmitters in high density networks (Recommendation ITU-R BT.655).

Accuracy of frequency measurements on random modulated signals depends on the statistics of the signal and the sample duration. Typically, the accuracy on a random modulated signal is one order of magnitude lower than on a pure sine wave (±10 Hz when locked on a 10^{-10} frequency standard). However, experience and simulations show that the above recommended measurement duration values ensure that frequency

measurement accuracy is at least an order of magnitude better – even on random modulated signals – than the precision required of transmitters for the various service categories defined in the RR.

In order to have a repeatable characterisation of the performance of a monitoring station, calibration and accuracy checks should be performed on pure sine wave signals.

A minimum instantaneous acquisition bandwidth should also be recommended for frequency measurement in monitoring stations. The measurement should be done with a filter sufficiently wide to contain the emission to be measured, but also sufficiently narrow to reject contributions from adjacent emissions.

Modern receivers include a number of filters (typically 10 or more) usually sufficient to provide a good filtering of common signals; however, one should be careful to select equipment that has sufficient bandwidth to accommodate signals to be monitored. One of the most common signals to be monitored being FM broadcast which should exhibit a frequency deviation not exceeding ±75 kHz one could require a monitoring station to have at least an instantaneous acquisition bandwidth of about ±200 kHz to ±300 kHz. A bandwidth of ±300 kHz is compatible with many modern digital signals, but not for signals such as DAB, IS95 or some high-speed point-to-point or point-to-multipoint systems such as rural telephony equipment used below 3 GHz, for which a bandwidth of 2 MHz is usually sufficient. Considering that higher bandwidth requires more costly digitisers and processors, one could recommend that instantaneous acquisition bandwidth for measurements should reach:

– about ±200 kHz for a low-grade monitoring station covering 9 kHz to 3 GHz;

– about ±2 MHz for high-grade monitoring station covering 9 kHz to 3 GHz.

Higher instantaneous bandwidths such as ±8 to ±10 MHz might be desirable in some cases, especially when monitoring above 3 GHz or monitoring Digital Video Broadcasting or signals of the mobile service.

5.2.2.5 FFT method

The FFT is an efficient method of converting digital amplitude versus time record into amplitude versus frequency spectral display, suitable method to make it by a microprocessor. Many modern spectrum analysers include digital processing of the IF integrating the receiver with FFT-based analysis.

FFT analysers for frequency measurement should have the following features:

– ZOOM FFT capability at the IF of the applied receiver, or high frequency resolution of the receiver;

– Hann- (Hanning-) window capability;

– an external frequency standard input for 5 or 10 MHz;

– at least 16-bit resolution;

– the frequency range should cover the range of the IF frequency of the receiver to be measured;

– remote control interface;

– averaging possibilities for measuring the frequencies of the noisy signals.

Nowadays, FFT becomes commonly used in measuring equipment (receiver or spectrum analyser). To reach better frequency accuracy, they may be driven by a frequency standard, for example, by an GNSS receiver embedded in the equipment. Excellent frequency resolution can be achieved by using ZOOM-FFT with Hann-weighting (windowing) function (see § 7.7).

There is a possibility to increase the resolution of the FFT-based frequency measurement by estimating that is counting the correct frequency from the power of spectrum lines around the detected peak in the power spectrum.

$$f_{estimated} = \frac{\sum_{i=j-3}^{j+3} l(i) \cdot i \cdot \Delta f}{\sum_{i=j-3}^{j+3} l(i)} \tag{5-6}$$

where:

j: array index of the apparent peak of the frequency of interest

i: array index of the current bin

$l(i)$: power of the current bin in linear units, e.g. Watt

Δf: Frequency spacing between FFT-bins, with $\Delta f = F_s/N$

N: number of FFT-bins.

The span $j \pm 3$ is reasonable because it represents a spread wider than the main lobe of the usually applied Hann-window. This calculation can reduce the measuring time significantly.

The advantages of the FFT-based measuring system are:

– the possibility of measuring frequencies of co- and even common-channel signals, e.g. in TDD networks;

– faster measurement speed for narrow resolution bandwidth;

– improved receiver sensitivity and frequency resolution compared to analogue receivers.

An example measurement is shown in Fig. 5-9. That measurement was made with a digital monitoring receiver, where the IFM technique is implemented within the receiver's software. The ADC sampling rate is 56 MSamples/s and the vertical resolution is 14 Bits. The accuracy of the (GPS-locked) frequency reference is ±20 ppb (parts per billion; $1 \cdot 10^{-9}$) and the tuning resolution is 0.01 Hz. The measurement is centred on a broadcast FM station at 89.7 MHz. The frequency span is 2 kHz, the RBW is 10 Hz and uses a Hanning window. With these conditions, the contributing factor of the measurement error include:

– error due to the frequency reference: the reference frequency accuracy times the centre frequency or $20\ \text{ppb} \cdot 89.7\ \text{MHz} = 1.794\ \text{Hz}$;

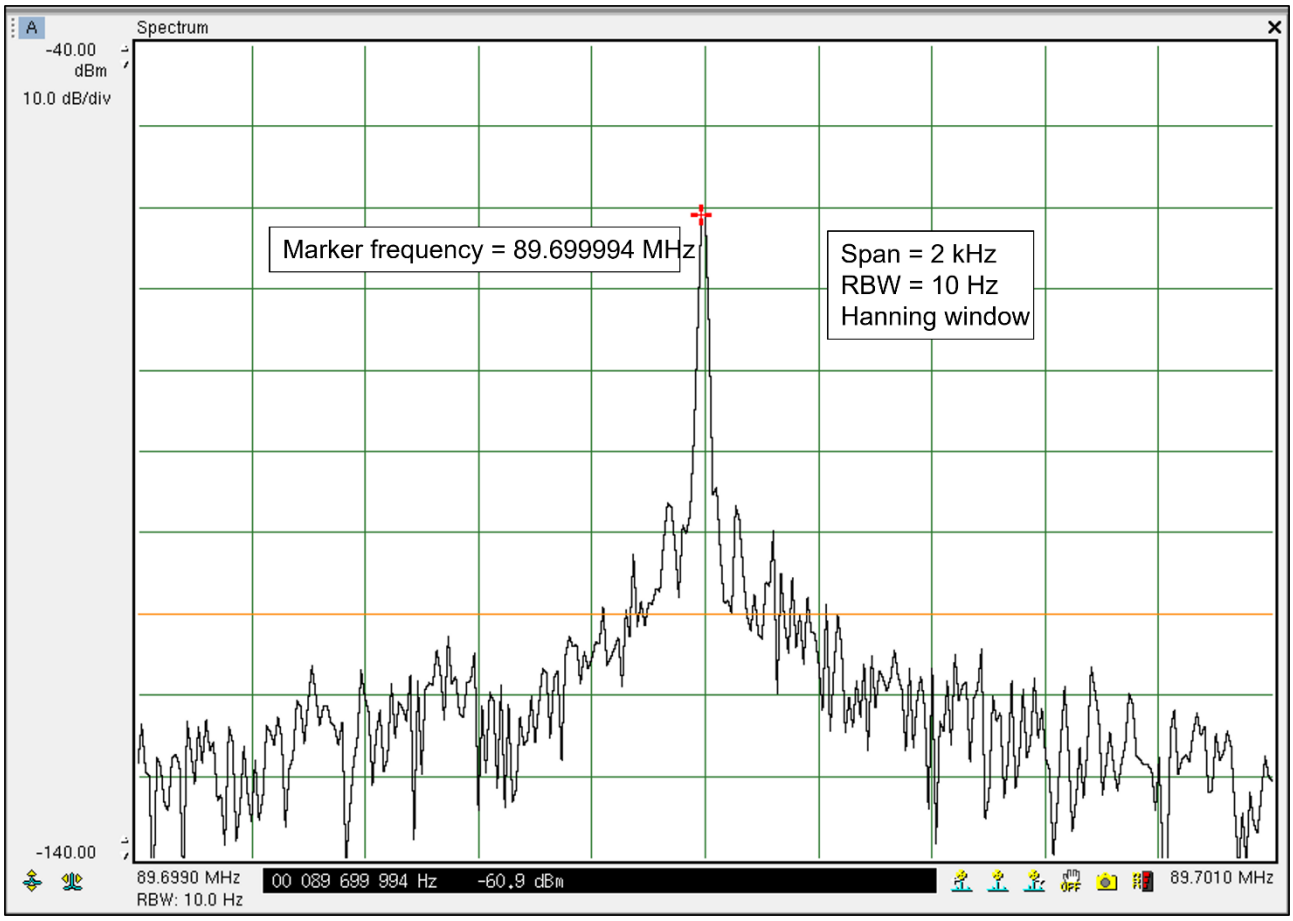
– error due to the frequency resolution: bin spacing of the Hanning window is approximately the RBW times 0.67: $10\ \text{Hz} \cdot 0.67 = 6.7\ \text{Hz}$;

– error due to the tuning resolution (0.01 Hz) does not contribute significantly to the error (the number is at least 10 times less than the error due the frequency reference).

The overall error indicates that this is a very accurate measurement of the carrier frequency of that radio station.

FIGURE 5-9

FFT Spectrum of an FM broadcast radio station carrier for IFM measurement



In a given implementation, the following additional advantages could be achieved with FFT-based measurements:

– easy tuning and adjustment to the frequency bands to be monitored (via computer terminal);

– adjustable to different accuracy requirements, e.g. as described by Recommendation ITU-R SM.377;

– digital storage of the spectrum data;

– high reliability due to the reduced number of mechanical components;

– reproducibility of all system settings due to digital processing;

– possibility of digitally transferring the data for further evaluation and/or processing;

– possibility to separately measure the frequency of carriers within densely populated frequency bands due to very narrow resolutions bandwidths.

NOTE – The position of the spectra at the IF output of the receiver must be taken into account in calculating the correct frequency.

For more details on FFT processing, see § 7.7: Fast Fourier transform.

5.2.3 Crystal-controlled stage of frequency measurement equipment against a standard frequency

All frequency-measuring instruments are provided with a crystal standard, regardless of whether the scale of a variable oscillator can be calibrated at particular points by a comparison with harmonics, or the final frequency is derived from the crystal standard, as is the case with the frequency synthesizers.

The output frequency of the crystal stage depends upon the ambient temperature and the operating voltage.

Even after the warm-up period, a crystal generator shows a steady variation of the output frequency.

At present, the order of magnitude of these variations ranges from 10^{-8} to 10^{-12}.

For good instrument, the steady variation of the crystal frequency is between 10^{-10} and 10^{-9} per day after a continuous warming-up time of several weeks.

Consequently, instrument crystal stages must be frequently compared with a frequency standard or must be controlled by a standard frequency emission.

An alternative to periodic comparison is to permanently lock the crystal to an atomic standard and in this way, combine the short-term stability of the crystal oscillator with the long-term stability of the atomic standard.

In instruments with high measurement accuracy the external crystal oscillator, or at least the oven of the internal crystal oscillator, should be continuously operated so as to avoid troublesome warm-up effects and discontinuity in the rate of aging.

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Application Note [AN_DMOD] Digital Modulation in Communications Systems – An Introduction. KEYSIGHT, Santa Rosa, CA, United States of America, downloadable at: Digital Modulation in Communications Systems | Keysight.

Application Note [FC_GUIDE], The RF Engineer's Essential Guide to Frequency Counters. Keysight, Santa Rosa, CA, United States of America.

BAUCH, A. and WHIBBERLEY, P. [PTB_GNSS], Reliable Time from GNSS Signals, InsideGNSS March/April 2017

ITU-R Recommendations

NOTE – In every case the latest edition of the Recommendation is encouraged to be used.

Recommendation ITU-R SM.377 – *Accuracy of frequency measurements at stations for international monitoring*

Recommendation ITU-R SM.1045 – *Frequency tolerance of transmitters*

Recommendation ITU-R BT.655 – *Radio-frequency protection ratios for AM vestigial sideband terrestrial television systems interfered with by unwanted analogue vision signals and their associated sound signals*

Recommendation ITU-R TF.768 – *Standard frequencies and time signals*

ITU-R Handbooks

Handbook on Selection and Use of Precise Frequency and Time Systems, Geneva, 2026

5.3 Measurement of RF level

5.3.1 Introduction

While in many cases monitoring stations require knowledge of the field strength or power flux-density (pfd) of an RF emission, the only parameter that can be measured directly is the RF level, either in terms of receiver input voltage or input power. Under certain conditions, the field strength can be calculated from the result of the level measurement.

RF level measurements of continuous emissions can be done either with a measurement receiver or a spectrum analyser. However, certain considerations apply when the signal to be measured is modulated. Furthermore,

digitally modulated signals often use time division multiple access (TDMA) and/or time division duplex (TDD). The resulting emissions are pulsed which makes the RF level measurement more complicated. Section 5.3 describes methods and equipment to be used by the monitoring service when measuring the RF level of continuous and pulsed signals.

5.3.2 Measurement detectors

Measurement receivers and spectrum analysers are usually able to interpret or weight the RF level using different measurement detectors. While the momentary amplitude of the RF signal constantly changes, the detector looks at the momentary RF amplitude for a certain time (the measurement time) and displays one single value as a result. Following are the most important detectors:

– *Peak detector (Pk)*

  Out of all momentary RF amplitudes in the measurement time, the Pk detector selects the highest and truncates all others.

– *RMS detector (RMS)*

  From all momentary RF levels, the RMS detector calculates the average power. This is equivalent to the thermal power of the RF signal.

– *Average detector (AV)*

  From all momentary RF levels, the AV detector calculates the average input voltage.

– *Quasi peak detector (QP)*

  The QP detector integrates all momentary RF levels as a weighting network with defined rise and fall times for pulsed signals. Its characteristics are defined in CISPR-16.

– *Sample detector (SA)*

  This is often the standard detector in spectrum analysers. For swept spectrum analysers, the measurement time on each frequency is the time necessary to sweep from one display point to the next (*sweep time/number of display points on x axis*). From all available momentary levels during this time, only the first is selected and all others are truncated.

It is important to understand that peak and RMS detectors indicate the *effective* RF level. This means that the readout of the peak detector would indicate the root mean square value of a sinusoidal signal having the same peak level as the measured signal, i. e. $U/\sqrt{2}$.

Figure 5-10 shows an example of the indicated level for different detectors when measuring an RF signal that is 100% AM modulated.

A thorough treatise on detector functions, detectors as standardized objects, trace functions and general aspects related to measurement receivers and spectrum analysers is found in [ERM-RM-270].

5.3.3 Level definitions

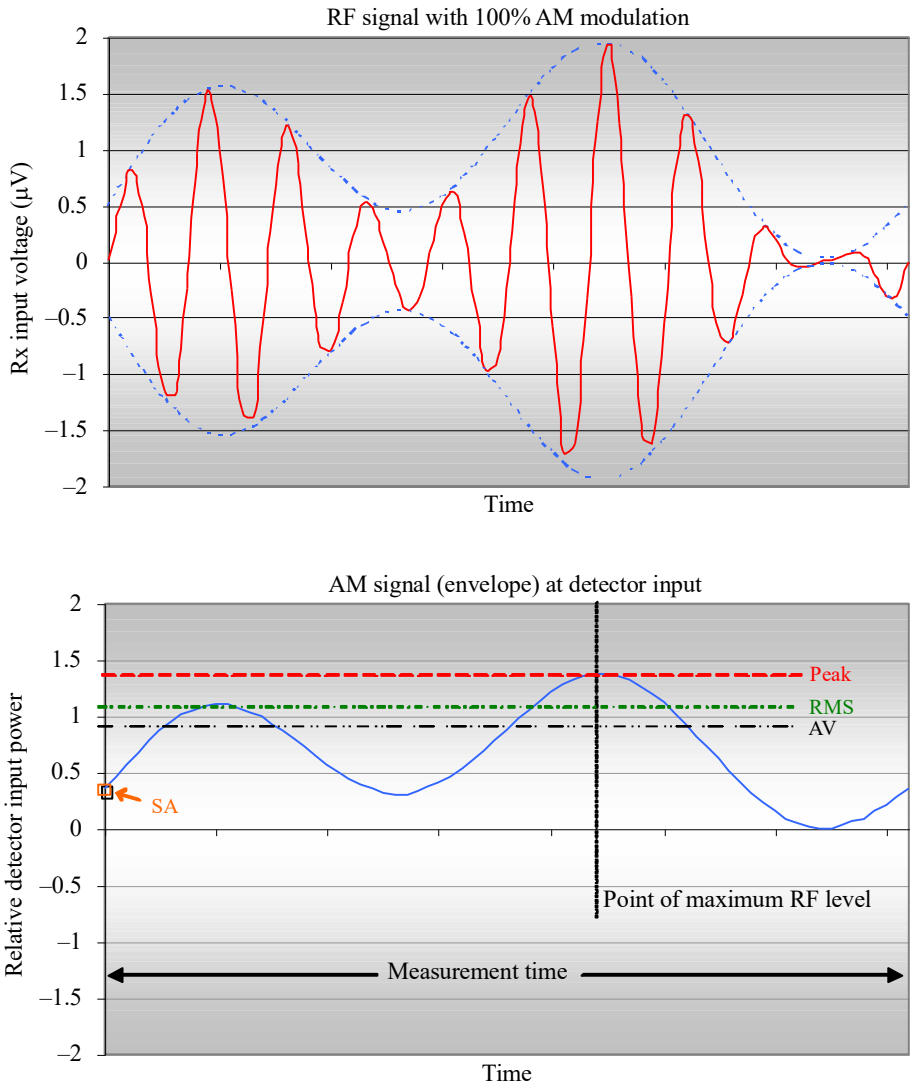
Many analogue and digital modulations such as AM, ASK, PSK, QAM and OFDM alter the amplitude of the RF signal. Therefore, when measuring these signals, the *kind* of level that should be measured needs consideration. The following levels are important:

– *Peak level:*

  This is the maximum level emitted. This level is important when the signal is regarded as an interferer, because usually the peak level determines the degree of the interference by radiations of electronic devices. It is measured with a peak detector and the MaxHold function (in case a spectrum analyser is used). The measurement procedure is the same for all signals, whether they are pulsed or continuous.

FIGURE 5-10

Indicated RF levels when measuring a 100% AM modulated signal



Spectrum-4.3-01

– *RMS level:*

This is the average power emitted. It specifies the energy contained in the signal and therefore determines whether a receiver can decode it or not. This is the most important level for continuous signals. Unless otherwise specified, always the RMS level is meant. It is also the reference level for network planning, coordination, compatibility studies and in licences for continuous signals. The RMS level is usually equal to the so-called channel power. It is measured with an RMS detector and a long integration time.

– *Average burst level:*

This is the average power (RMS) *during a burst* when the signal is pulsed (e.g. from TDMA systems). The RMS measurement with a long integration time would normally average bursts and pauses, leading to results that depend on the timing. However, for pulsed digital signals the most important level is the RMS level measured only during the burst and sparing out the pauses. Unless otherwise specified, the average burst level is meant if the signals are pulsed. It is also the reference level for network planning, coordination, compatibility studies and in licences for pulsed signals. It is measured with an RMS detector and an integration time that is shorter than (or equal to) the burst. The measurement has to be time synchronized with the pulses of the signal.

– *QuasiPeak level:*

This level is especially used to characterize the disturbing effect of unwanted signals regardless of whether they are pulsed or continuous. The maximum QP level of electrical devices is defined in relevant standards. Due to the defined weighting characteristic of the detector, the QP level of a pulsed signal depends on the peak level during a pulse, the pulse length and its repetition frequency. It is measured with a pre-defined bandwidth (200 Hz, 9 kHz or 120 kHz depending on the frequency range) and integration time. Modern measurement receivers usually set both parameters automatically when the QP detector is deployed. In order to get qualified QP-readings that can be compared to the relevant standards the measurement receiver also has to fulfil the requirements given in CISPR 16.

5.3.4 Influence of modulation

Some modulations alter the amplitude of the signal while others do not. This fact has great influence on the way the signal level can be measured.

For unmodulated signals and continuous signals having modulations with constant amplitude such as FM, MSK and FSK, all detectors show the same reading. In this case, Pk, RMS, AV and QP levels equal.

If the modulation alters the RF amplitude such as AM, SSB, ASK, PSK, QAM and OFDM, all detectors show different readings. In this case, it is necessary to carefully consider the level required when selecting the measurement detector, equipment and method.

The average burst measurement for systems that alter the amplitude require time synchronized measurement, making sure that pauses are spared. This function is not always available in spectrum analysers or measurement receivers.

It is, however, easy to determine whether the modulation alters the amplitude or not. Using a spectrum analyser in zero span mode (resolution bandwidth ≥ signal bandwidth), a certain time interval (for pulsed signals: at least one burst) is captured in ClearWrite mode. If the amplitude remains constant over time, the modulation is FM, FSK or MSK, otherwise the amplitude is modulated (AM, SSB, ASK, PSK, QAM, OFDM).

Figure 5-11 shows an example of a GSM/EDGE signal in the time domain (zero span). The first time slot (burst) is a standard GSM burst with GMSK modulation (constant amplitude); the second slot is an EDGE burst using 8-PSK modulation that alters the amplitude.

5.3.5 Necessary measurement bandwidth

For direct level measurements of modulated signals, the measurement bandwidth has to be at least as wide as the occupied bandwidth of the signal. Depending on the type of equipment, the measurement bandwidth can be called

– IF bandwidth (in case of a conventional measurement receiver).

– Resolution bandwidth (RBW, in case of a spectrum analyser).

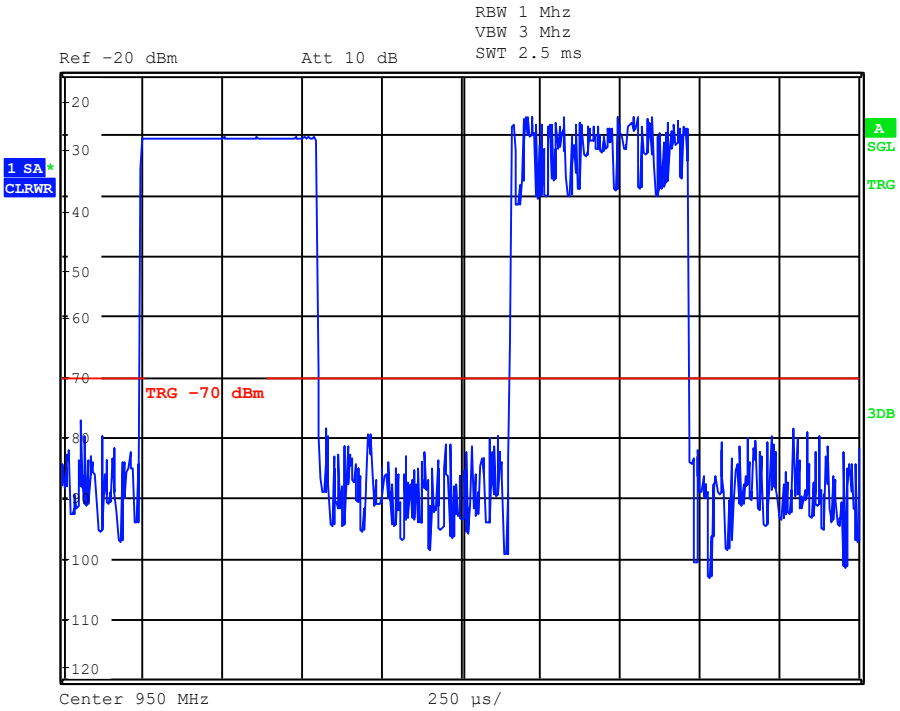
– Acquisition bandwidth (in case of an FFT analyser).

Therefore, knowledge of the occupied bandwidth is necessary prior to measuring the level of a modulated signal. The widest available measurement bandwidth of the equipment limits the broadest signals that can be measured. One exception is the RMS level of continuous signals inside a used channel. Most modern spectrum analysers can measure this level using smaller resolution bandwidths and integrating the spectral levels over a wide frequency range (channel power mode).

Table 5-2 shows necessary measurement bandwidths for some common radio systems.

FIGURE 5-11

Pulsed signal with and without amplitude modulation



Spectrum-4.3-02

TABLE 5-2

Necessary measurement bandwidths

System	Necessary measurement bandwidth	Remarks
AM double sideband	9 or 10 kHz	Narrowband (voice) transmissions
AM single sideband	2.4 kHz	Narrowband (voice) transmissions
FM narrowband with a channel spacing of: 12.5 kHz 20 or 25 kHz	 7.5 kHz 12 kHz	
FM sound broadcasting	120 kHz	Maximum occupied bandwidth is 180 kHz, but nearly all of the energy is within 120 kHz
T-DAB, T-DMB	1.5 MHz	
Analogue TV	120 kHz	Although occupied bandwidth is higher, nearly all energy is in the vision carrier for which 120 kHz is sufficient
Digital terrestrial TV	6, 7 or 8 MHz	Equal to the channel bandwidth used
TETRA	30 kHz	
GSM, EC-GSM-IoT	300 kHz	Although common channel spacing is 200 kHz, the occupied bandwidth of GSM signals is higher
NB-IoT	180 kHz	
LTE-M	1.08 MHz	Machine Type Communication, LTE-Cat M1; Nominal Bandwidth: 1.4 MHz
LTE (4G)	3, 5, 10 or 20 MHz	Depending on system configuration (equal to maximum emission bandwidth)

TABLE 5-2 *(end)*

System	Necessary measurement bandwidth	Remarks
5G NR (Frequency Range FR1: 450 MHz – 6000 MHz)	5, 10, 15, 20, 25, 30, 40, 50, 60, 80, 90, 100	Depending on system configuration (equal to maximum emission bandwidth)
5G NR (Frequency Range FR2: 24250 MHz – 52600 MHz)	50, 100, 200, 400	Depending on system configuration (equal to maximum emission bandwidth)

5.3.6 Measurement procedure with a measurement receiver

A measurement receiver can normally measure the peak, RMS, AV and QP levels of a signal. All four levels can directly be measured using the correct measurement bandwidth (see § 5.3.5), the respective detector and a long integration time (measurement time).

When the signal is pulsed, the RMS reading only provides the "long-term" average power where pulses and pauses are averaged. When the signal is FSK or MSK modulated, the peak reading is also the average burst level. For other modulations, the average burst level can be calculated from the long-term RMS reading, provided the pulse/pause ratio remains constant over the whole measurement time:

$$P_{av-burst} = P_{RMS} + 10 \cdot \log(T/\tau) \tag{5-7}$$

where:

$P_{av\text{-}burst}$: average burst level (dBm)

P_{RMS} : long term RMS level reading of the receiver (dBm)

T : burst period (s)

τ : burst length (s).

If not known, T and τ can be measured using any standard spectrum analyser in zero span mode or an oscilloscope connected to the IF of the measurement receiver.

5.3.7 Measurement procedure with swept spectrum analyser

The optimum RBW to display the actual spectrum of a signal with an analyser is about *span/sweep points*. This setting, however, cannot be used to directly measure any level of a modulated signal. For level measurements the RBW has to be at least as wide as the signal bandwidth. The resulting display will not show the true spectrum, but it allows reading of the level using a marker set to the highest point of the displayed trace.

The peak level of pulsed and continuous emissions can be measured with the peak detector and MaxHold function either in the frequency or time domain (In both cases: RBW ≥ signal bandwidth).

The RMS level of continuous signals can be measured with an RMS detector, the ClearWrite function (not MaxHold) and a long sweep time. If no true RMS detector is available, the sample detector can also be used in conjunction with linear trace averaging.

For the RMS level, most modern spectrum analysers have a built-in function that measures the power inside certain frequency boundaries. This function is often called channel power measurement. It records the momentary spectrum (ClearWrite function) with a small RBW and integrates the spectral power levels over the desired frequency range. While this function works fine with continuous signals, even if neighbouring frequencies are occupied, it fails if we have pulsed signals. This is because the time needed by the analyser to sweep over the channel is longer than the pulse. Therefore, the recorded level drops to the noise floor during every pause, resulting in a false spectrum and hence false power integration. This measurement needs the RMS or sample detector. The MaxHold function cannot be used.

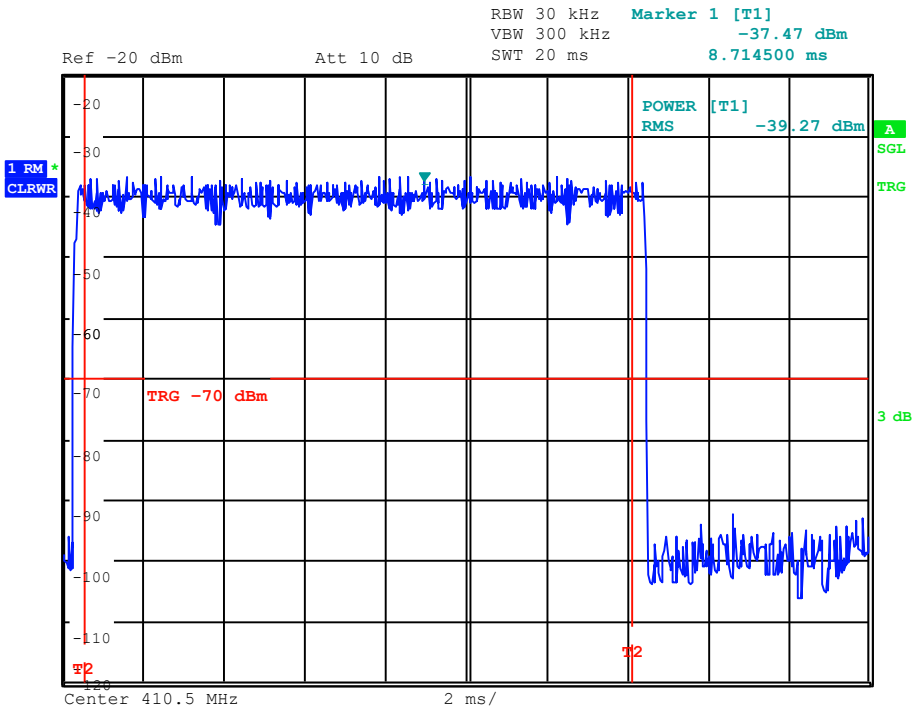
The preferred way to measure the AV-burst level with a spectrum analyser is in the time domain. Again, if the signal is FM, FSK or MSK modulated with constant amplitude, the AV-burst level is equal to the peak level

and further measurements are not necessary. For the other modulations, however, we need to synchronize the measurement with the signal to make sure that the measurement is only active during a burst. This function may be called "time domain power measurement". At least one burst of the signal is captured in zero span with RBW ≥ signal bandwidth and RMS or sample detector. Then, the measurement function calculates the RMS level over the whole burst. This can either be done by adjusting the sweep time so that the burst fills the whole screen, or, if the analyser provides the possibility, by setting limits in time that mark the start and end points for the calculation.

Figure 5-12 shows a time domain power measurement of a TETRA signal. Every pixel of the trace is already a momentary RMS level because the RMS detector was used. Only those pixels that are between the two time lines T1 and T2 are integrated and result in the indicated AV-burst power of −39.27 dBm.

FIGURE 5-12

Time domain power measurement of average burst level



Spectrum-4.3-03

5.3.8 Measurement with an FFT analyser

Modern FFT or real-time analysers usually acquire the signal in a bandwidth that is in any case wider than the signal bandwidth, and calculate spectral and total levels using FFT algorithms. The user has great flexibility over the acquisition time, bandwidth and analysis length. As the default, the level indicated is the average power during the acquisition time which corresponds to the RMS level.

The peak level can be measured by selecting the shortest acquisition time possible and using a MaxHold trace function over multiple consecutive FFTs.

Together with the possibility to trigger the acquisition at the burst start, the variable acquisition time makes it possible to synchronize the equipment in a way that only the bursts are analysed, sparing out the pauses. Other than a swept spectrum analyser where the minimum sweep time is determined by the RBW filter, the FFT analyser can display the true spectrum of a signal even if only a very short snapshot can be taken. The necessary acquisition time is usually much shorter than burst lengths of digitally modulated signals, so the FFT analyser can also measure the AV-burst level in the frequency domain using a triggered channel power measurement function.

Figure 5-13 shows a burst from an 802.11g WLAN router with COFDM modulation. The left-hand window (Time overview) shows amplitude vs. time of the signal for the whole capture or acquisition. The blue line on the top shows the time where the signal is analysed (50 µs) which is only part of the total acquisition time.

The analysis time has been placed in the acquisition time window such a way that only the burst is analysed. The right side of Fig. 5-13 shows the channel power measurement in the frequency domain.

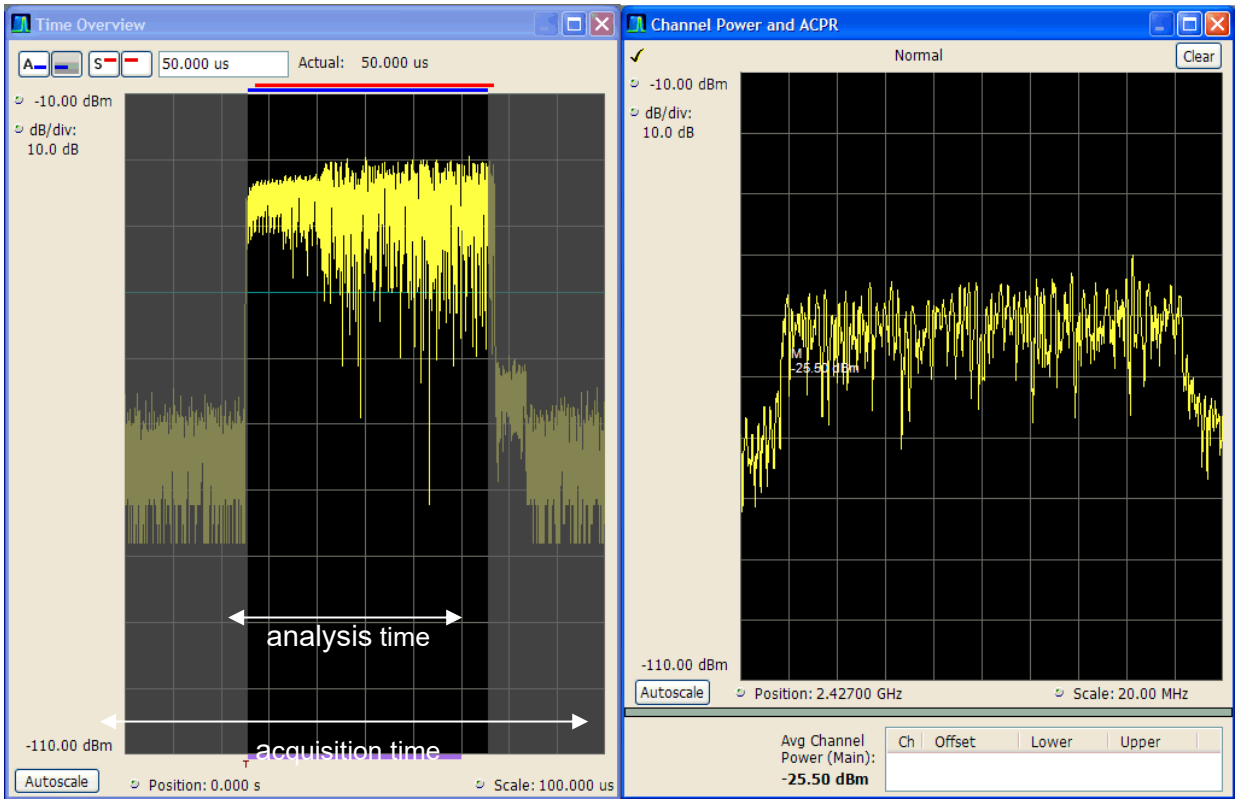
This method works with the FFT analyser because the actual measurement is only performed during the analysis time (= burst time). Therefore, the indicated channel power (−25.5 dBm) is in fact the AV-burst power.

It should be noted that some modern wideband monitoring receivers are also capable of performing the functions of an FFT analyser. This type of equipment is equally suited for the measurements described in this section.

More details regarding how and why the (Fast) Fourier Transform works and where common pitfalls need to be understood can be found in § 7.7 and [FFP].

FIGURE 5-13

AV-burst measurement in the frequency domain with an FFT analyser



Spectrum-4.3-04

5.3.9 Correction for wide band signals

Especially digital signals are sometimes wider in bandwidth than the highest measurement bandwidth available to the equipment. If the RF energy of the signal is evenly spread over the whole bandwidth, like in OFDM systems, all levels can also be measured using a smaller measurement bandwidth and correcting the result with the following formula:

$$P = P_m + 10 \cdot \log(signal\ bandwidth/RBW) \tag{5-8}$$

where:

P : total signal level in dBm

P_m : measured level in a smaller RBW.

This method can also help if strong signals on neighbouring frequencies are present and would otherwise influence the result.

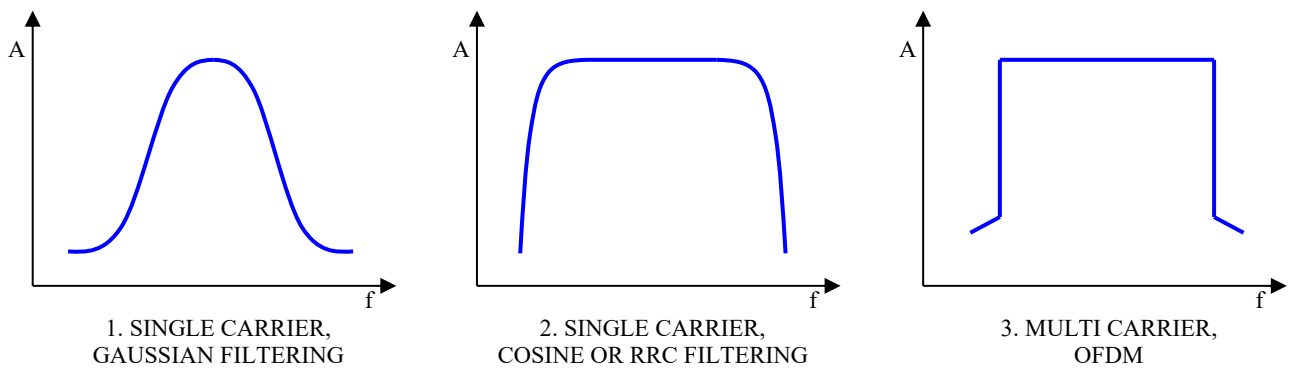
However, it is only applicable to OFDM modulated signals and, with a certain error of usually less than 1 dB, to single carrier digital signals having cosine or root raised cosine (RRC) filtering. It cannot be applied to digital signals using Gaussian filtering.

Figure 5-14 shows the typical spectra of digital signals.

Analogue modulated signals can have a variety of spectral shapes, but measuring with small bandwidths and correction to the signal bandwidth is generally not possible.

FIGURE 5-14

Typical spectra of digital signals



5.3.10 Channel power and adjacent channel power measurement

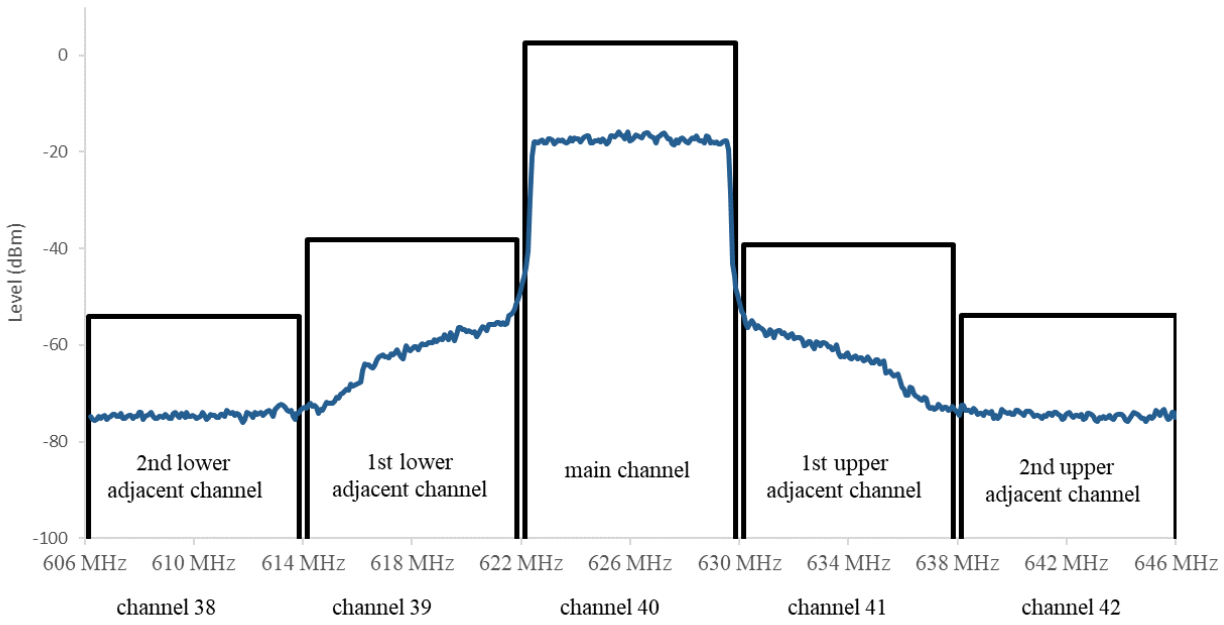
The terms "channel power" and "adjacent channel power" refer to the r.m.s power within a rectangular bandwidth in the frequency domain. The measurement result represents the effective power of a transmitter within its operating channel and its adjacent channels. The terminology can be found in Fig. 5-15.

The results can be represented in a few different ways: the unit of the transmitter's power on the main channel power is usually expressed as an absolute value, e.g. dB(mW) or dB(W). Sometimes it is preferred to state a power spectral density with the unit $dB(mW)/Hz$ or e.g. dB(mW)/1 MHz.

The units of the adjacent channel's power can be expressed as absolute values, like −30 dB(mW) or values relative to the main channel; for example, $+47\ \mathrm{dB(mW)} - (-30\ \mathrm{dB(mW)}) = -77\ \mathrm{dBr}$. The relative measures are sometimes called 'adjacent channel power ratio' (ACPR) or 'adjacent channel leakage ratio' (ACLR).

FIGURE 5-15

Channel naming scheme used for channel power measurements



There are two options to perform the measurement:

a) by integration of many power readings using a small measurement bandwidth to encompass the large channel bandwidth. This has the benefit of achieving sharper edges (or better selectivity) between channels due to the narrower filter characteristics;

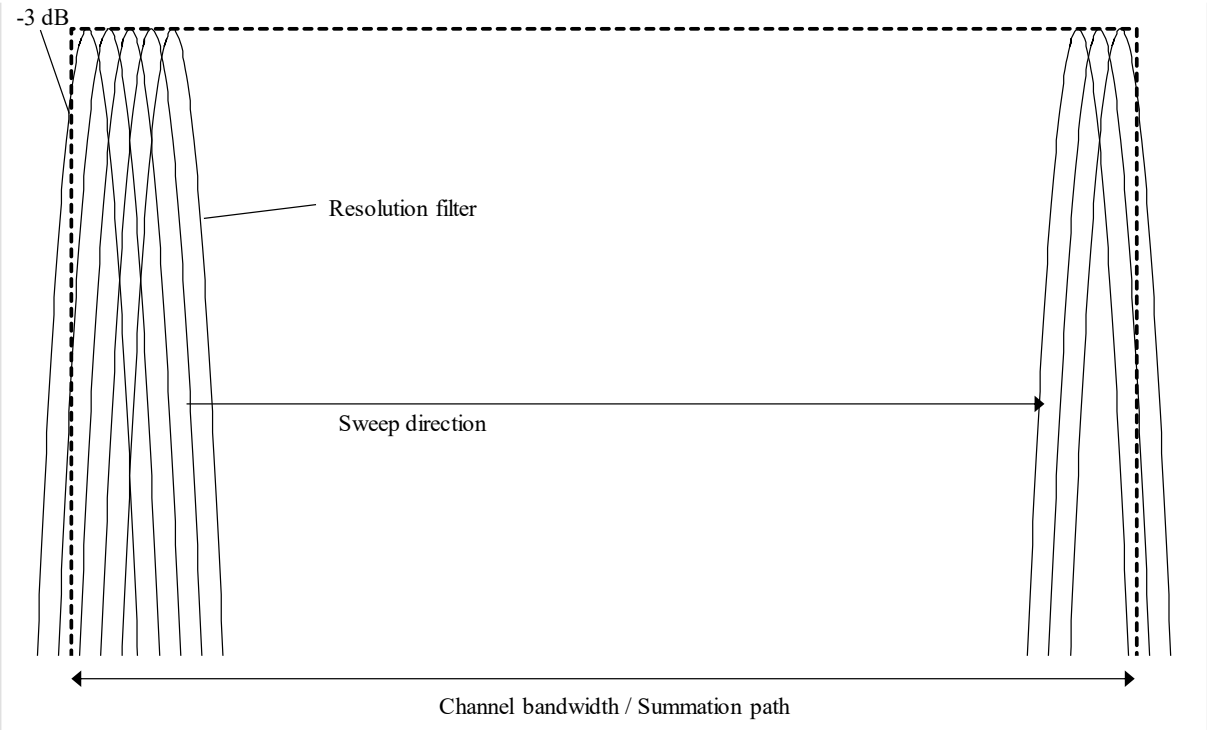
b) by measuring the IF voltage in the time domain (zero span) with IF filters dedicated to the channel power definitions of a specific radio system.

Method (a) is the "integration bandwidth" method (IBW), while method (b) is sometimes called "Fast Channel Power" method. While (b) is straightforward, no specific explanations are needed. Method (b) is applicable only if the required filters are available at the measurement instrument and can separate adjacent channels. Method (a) works independent of the channel's bandwidth and is usable if the adjacent channels are occupied without any special needs regarding the available resolution bandwidth filters. As usual for all r.m.s. measurements, the results can be stabilized by choosing longer measurement times. Care should be taken not to use the MaxHold function to stabilise the trace as this would lead to incorrect results. The time needed to reach a certain accuracy is lower for the fast channel Power method as compared to the IBW method. Furthermore, the IBW method cannot be used on pulsed signals such as digital TDMA/TDD systems unless a gated measurement function is available allowing to limit the measurement to the burst time only.

The IBW (integration bandwidth) method measures the channel power by segmenting the whole channel bandwidth into many small bandwidth measurements along the desired frequency range. These partial powers are summed until the desired channel bandwidth is covered (see Fig. 5-16). Typically, the resolution bandwidth and frequency stepsize is chosen to be about 1 % of the channel bandwidth. This leads to a good selectivity with respect to the adjacent channels and a sufficient number of samples for the integration process. This can also be applied to cases where the adjacent channel bandwidth is different to the main emission's channel bandwidth.

FIGURE 5-16

Channel power measurement with the integration bandwidth (IBW) method



After sampling the channel, the levels of the individual bins are integrated as given in the following equation:

$$p_{channel} = 10\log\left(\frac{BW_{channel}}{RBW \cdot N \cdot k}\right) + 10\log\left(\sum_{i=0}^{N-1} 10^{p_i/10}\right) \tag{5-9}$$

where:

$p_{channel}$: channel power (in the unit given by p_i)

$BW_{channel}$: channel bandwidth, in Hertz

RBW : the resolution bandwidth, in Hertz

N : number of frequency bins used

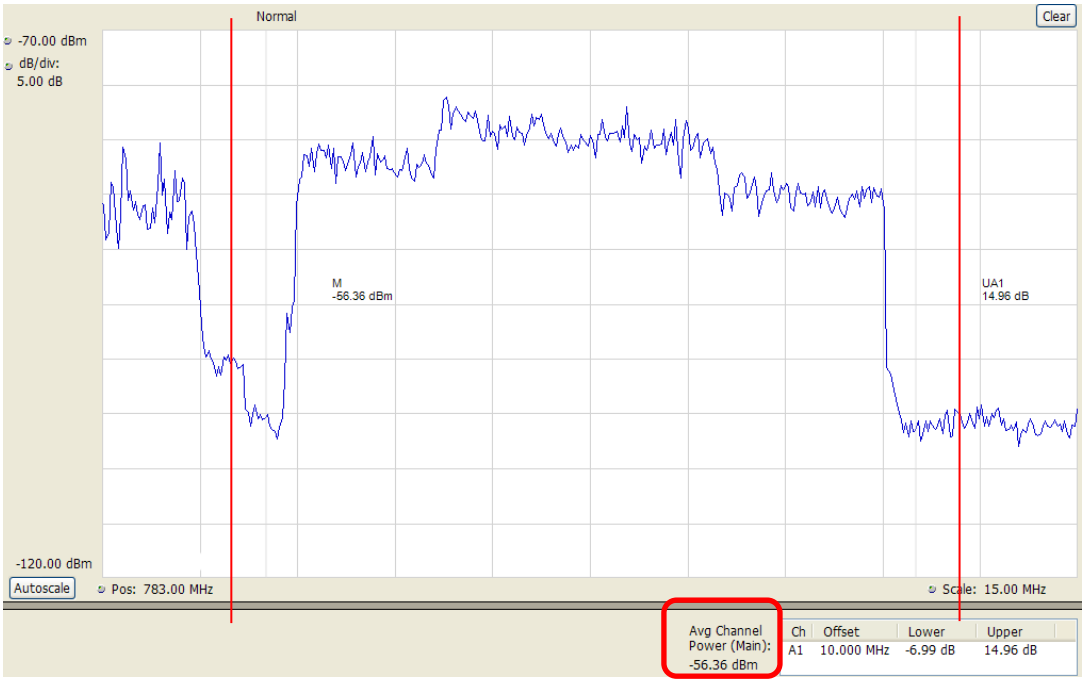
k : correction factor from the filter's bandwidth towards its rectangular equivalent noise bandwidth

p_i : the power of the i-th element on the deciBel scale

Figure 5-17 shows an example of a channel power measurement on an LTE signal using the IBW method. Only spectral power densities between the red vertical lines are used to calculate the channel power. The result is indicated in the red circle.

FIGURE 5-17

Channel power measurement example using the IBW method



Many modern spectrum analysers, monitoring receivers, and vector signal analysis software packages have adjacent power measurement features that can be configured to make these measurements automatically for a variety of radio standards.

5.3.11 Typical problems encountered

5.3.11.1 Unwanted signals on neighbour frequencies

Level measurements with a measurement receiver or direct measurements with a swept spectrum analyser only deliver accurate results when signals on neighbouring frequencies are sufficiently suppressed. In typical monitoring situations this is often not the case. Since the measurement bandwidth has to be at least as wide as the signal bandwidth and the measurement filter usually has Gaussian shape, it captures a lot of energy from neighbouring channels as well. If a signal on a neighbouring channel is stronger than the wanted signal, the direct level measurement may be impossible.

One way to overcome this problem is deliberately measuring with a small measurement bandwidth and correction to the signal bandwidth using equation (5-8), but this works only for signals with the energy evenly spread over the whole spectrum (OFDM and broadband signals with cosine or RRC filtering).

Another method that works in the presence of neighbouring signals is the channel power function implemented in most spectrum analysers, but this can only be used to measure the RMS level and is limited to continuous signals.

Only the FFT analyser can measure all levels including AV-burst in any case. It works independent of the modulation type of the signal, nearly independent of the signal bandwidth, and also in the presence of strong signals on neighbouring frequencies.

5.3.11.2 Low signal to noise ratios

Each of the discussed measurement methods requires a sufficiently high (S/N) in order to produce accurate results. Some monitoring tasks, however, also require level measurement of signals that are very weak and close to the system noise. In these cases, a correction for the system noise can be applied under certain conditions. This correction depends on the S/N, the detector, the shape of the measurement filter and sometimes even the modulation of the wanted signal.

Figure 5-18 shows the necessary corrections for peak, RMS and AV levels of continuous signals when the measurement filter has a Gaussian characteristic.

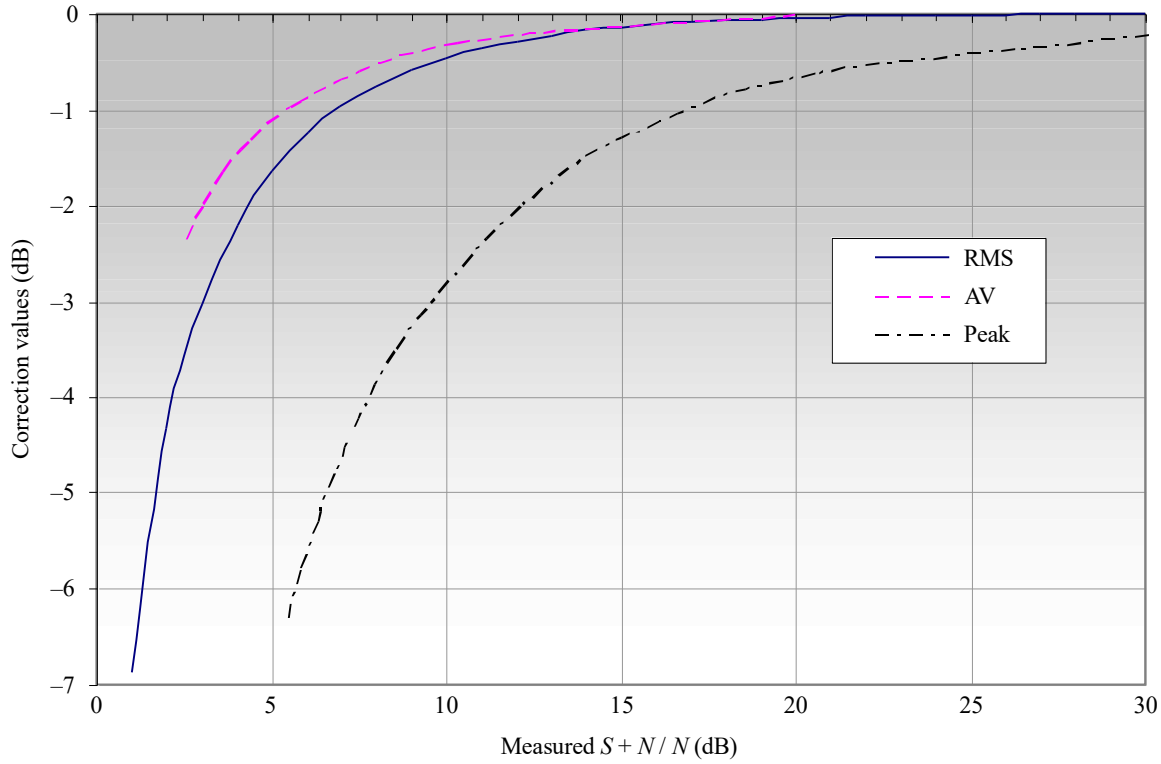
The values for the AV and Peak detector in Fig. 5-18 only apply to wanted signals with constant RF amplitude (unmodulated carriers, FM, FSK, (G)MSK). For amplitude modulated signals, the corrections to AV and Peak detector values depend on the actual signal (e.g. type of modulation, coding) and cannot be generalized.

For average burst levels, the RMS correction applies.

Long-term RMS or AV levels of pulsed signals cannot be corrected as the necessary correction value would also depend on pulse length and pulse repetition frequency. The same applies to QP levels.

FIGURE 5-18

Corrections to indicated level measured under low *S*/*N* ratios



Spectrum-4.3-06

The correction values in Fig. 5-18 have to be added to the measured signal level. Because the correction is negative, the actual signal level is lower than measured.

Table 5-3 summarizes the minimum (*S*+*N*/*N*) conditions under which level measurements can be made without correction under the condition that the measurement accuracy is better than 1 dB.

TABLE 5-3

Minimum (*S*+*N*/*N*) for 1 dB level measurement accuracy

	Minimum (*S*+*N*/*N*) for 1 dB accuracy		
Modulation	**AV (dB)**	**RMS (dB)**	**Peak (dB)**
Unmodulated carrier (N0N)	6	8	18
Constant amplitude (FM, FSK, MSK)	6	8	18
Amplitude modulated (AM, ASK, PSK, QAM, OFDM)	6	8	14

Generally speaking, the limits of the own system and the signal to be measured should be tested before blind corrections are applied. The key idea for those corrections is that the power level displayed on the instrument is always a superposition of the instruments intrinsic noise and the external signal given by:

$$p_{display} = 10 \cdot \log(P_{noise} + P_{signal}) \tag{5-9}$$

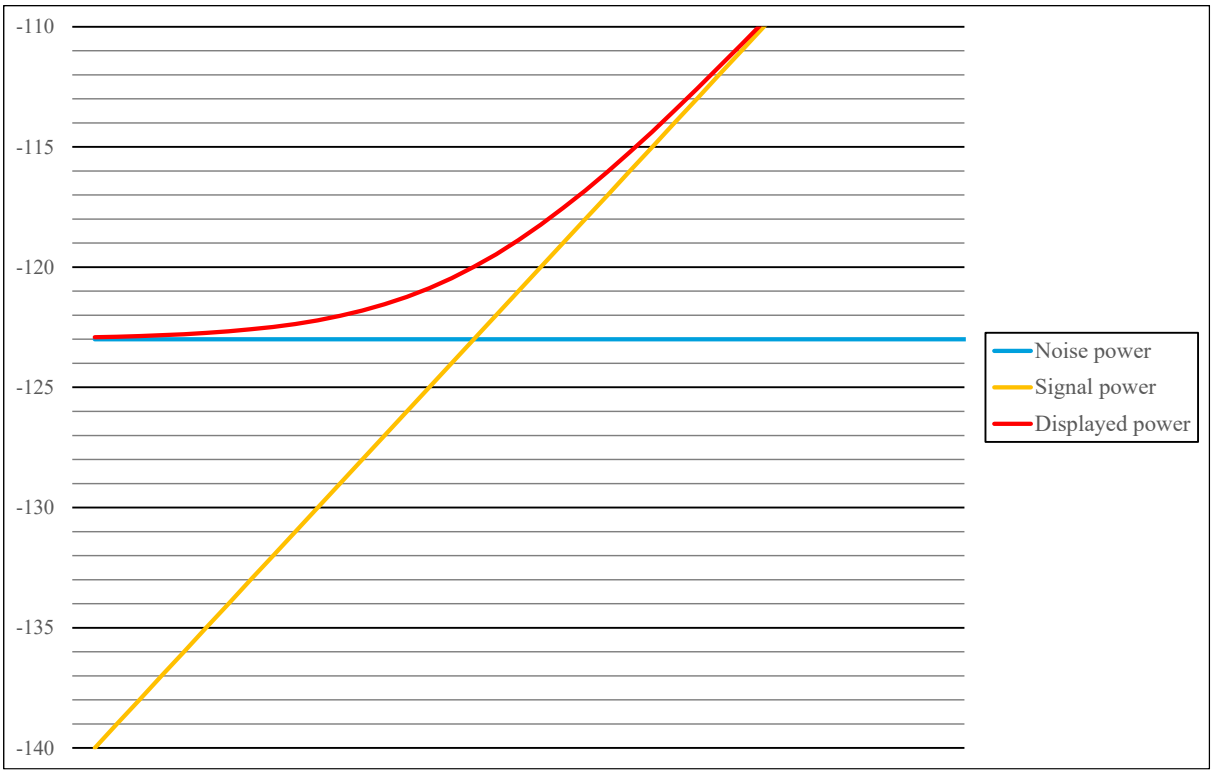
Assuming that the noise-level is constant over a short time (a few minutes) leads to:

$$p_{signal} = 10 \cdot \log(10^{(p_{display}/10)} - 10^{(p_{noise}/10)}) \tag{5-10}$$

The relationship between these three parameters is shown in Fig. 5-19.

FIGURE 5-19

Level displayed on an instrument as a function of the instrument noise and input signal level



5.3.11.3 Measurements of levels below the noise floor

Introduction

There are passive services which operate at power flux-density (pfd) levels below the noise floor. Consequently, they require protection from unwanted emissions or other forms of radiation below the noise floor.

Passive services such as the radio astronomy service, perform measurements using multiple probes which are processed in such a way that random noise cancels itself out, whereas the wanted signals appear out of the decreasing noise. That is why pfd limits have been agreed with the values below recognized levels of thermal noise, see Recommendation ITU-R RA.769. Especially those services will get severely impaired or even blind if the interference is not monitored and subsequent action taken. For that monitoring stations sometimes need to use similar techniques to discover the interference hidden in noise.

Principle

In order to monitor a wanted signal below the noise level, a series containing a high number of spectra in which the wanted signal is present needs to be taken, digitized, stored and averaged (say on the order of tens of thousands). The same number of spectra without the wanted signal, but containing the same sort of random noise, need also to be taken, digitised, stored and averaged but then inverted. The two different series of spectra can be obtained either by changing the antenna pointing or, if the wanted signal is of burst type, by taking them during both on and off times. In the resulting two processed spectra, the noise will have been considerably suppressed, and other signals of unknown origin may be visible due to the inversion. More information about this technique is available in Recommendation ITU-R SM.1681.

Caveats

While radio-astronomy researchers rely on very sophisticated and manually selected instruments, radio monitoring services usually rely on general purpose instruments. For that, some prior checks should be done during preparation of such measurement applications. Figure 5-20 shows the Allen-variance of the noise level at a spectrum analysers input as a function of the integration/averaging time. The record starts right after the devices self-alignment routines have finished. The different lines represent the instruments different warm-up periods prior to the measurement. It can be seen that:

– the instrument need approx. 100 seconds after the alignment to give the stable most level readings;

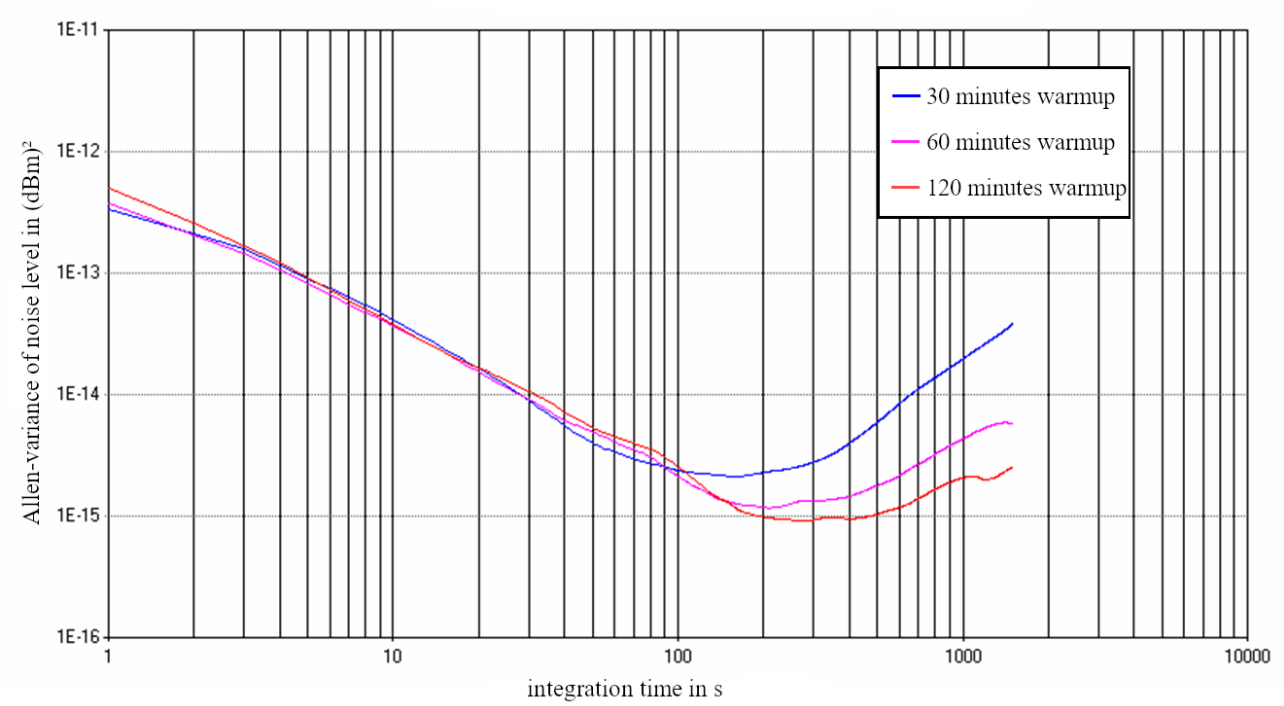
– longer warmup-periods support result stability, but there are upper limits;

– longer warm-ups prolong the sweet spot where the level stability is highest;

– after a certain amount of time, the instrument starts to drift.

FIGURE 5-20

Allen-variance of long-term averaged noise level



5.3.12 Calibration of measurement equipment

Calibration of measurement equipment may be made with a CW standard signal generator tuneable over the desired frequency range, an impulse generator or a random noise generator of known and stable output characteristics and having an output impedance matched to the receiver's input impedance with which it is to be used.

The output level of CW signal generators can be calibrated using RF power meters. For adaptation of the output power to the required receiver input level the use of calibrated attenuators is recommended. Calibration is the result of a series of measurements, for the characteristics of the instrument to be calibrated are always functions of frequency and of signal level. Stray pickup because of poor shielding, through power circuit cables, discontinuities in cabinet shielding, etc., may reduce the accuracy of the readings in some cases.

Many measurement equipment has built-in calibration and self-test functions for a detection of errors and deviations which may prevent the unintentional collection of erroneous data over a long time. Regular use of such self-tests and additional periodic calibration using external references and standards is recommended, as discussed in § 2.3.4.

5.3.13 Measurement errors

The accuracy obtainable includes both systematic and stochastic errors. The amplitude response of a well-designed synchronous detector does not contain any systematic errors. A systematic approach to describe measurement uncertainty is given in § 7.9.

Analogue selective level meters and spectrum analysers can have systematic errors caused by the shape of the selectivity curve, sweep rate and detector response. The actual errors will depend upon the particular design and method of application.

FFT signal analysers have an inherent but predictable amplitude error caused by the finite sampling interval time. The amplitude of the error depends on the ratio of the digital channel sampling frequency to the signal frequency, as well as the actual weighting factor used in the equipment. In the worst case, the FFT processing amplitude error, when Hamming weighting is used, does not exceed 1.5 dB [RANDALL_1977]. This systematic error can easily be compensated for, during signal processing, by means of the software program.

It should be noted that as the receiver is tuned to a fixed frequency while the signal analyser scans the passband of the receiver, any ripple in the IF passband response of the receiver will be a source of error.

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RANDALL, R. B. [RANDALL_1977] Application of B&K Equipment to Frequency Analysis. Brüel & Kjaer, 17-089, ISBN 978-8787355148

ETSI [ETSI TR 103 581]: TR 103 581 Use of measurement detectors in radio measurement methods, Sophia Antipolis Cedex, 2019

BUTZ, TILMAN: [FFP]: Fourier Transformation for Pedestrians. Springer Nature Switzerland AG, 2015, ISBN 978-3-319-16984-2

ITU-R Recommendations and Reports

NOTE – In every case the latest edition of the Recommendation and Report is encouraged to be used.

Recommendation ITU-R SM.1681 – *Measuring of low-level emissions from space stations at monitoring earth stations using noise reduction techniques*

Recommendation ITU-R RA.769 – *Protection criteria used for radio astronomical measurements*

Report ITU-R BS.516 – *Field strength resulting from several electromagnetic fields*.

5.4 Measurement of field strength and pfd

5.4.1 General considerations

Introduction

In many cases, the monitoring service has to determine the field strength or power flux-density of an emission. These parameters are generally calculated from RF level measurements which are described in § 5.3. The procedures to determine field strength or pfd are based on the procedures and results of the RF level measurement.

The terms “measurement of field strength” and “measurement of pfd” as used herein are intended to apply to four general categories of measurement:

– measurements performed with portable or mobile facilities, to obtain relatively instantaneous or short-term data at one or several locations;

– measurements performed with mobile facilities to obtain statistical parameters of coverage in the field of mobile radio;

– short-term measurements at a fixed location, generally in support of other monitoring operations;

– long-term measurements involving field strength recordings and analysis of chart records, respectively storage and analysis of measured data using computers.

Purpose of measurements

Measurements of field strength and pfd are generally made for one or more of several purposes including:

– to determine the adequacy of a radio signal strength and the effectiveness of the source of an emission (e.g. a transmitter) for a given service;

– to determine the interference effects of a given intentional radio emission (electromagnetic compatibility);

– to determine the signal strength and interference effects of unintentional emissions of any wave shape from equipment which radiates electromagnetic energy, and to assess the effectiveness of suppression measures;

– to measure propagation phenomena, for the development and verification of propagation models;

– to ensure compliance with the relevant RR;

– to assess the human exposure to electromagnetic fields.

Approximate field strength values for a specific receiving site can be obtained using prediction methods and computer models. It is, however, important to remember that there are many unknown factors which necessitate and/or justify on-site measurements. Under realistic conditions propagation of radio waves shows deterministic behaviour with superimposed random space and time dependence.

Influence quantities to take into account for the measurement of field strength and power flux-density are:

– receiver reading;

– attenuation of the connection between antenna and receiver;

– antenna factor;

– receiver sine-wave voltage accuracy;

– receiver selectivity relative to occupied bandwidth;

– receiver noise floor;

– mismatch effects between antenna port and receiver;

– antenna factor frequency interpolation;

– antenna factor variation with height above ground and other mutual coupling effects;

– antenna directivity;

– antenna cross-polarisation response;

– antenna balance;

– shadowing and reflections due to obstacles.

This section on field strength and pfd measurements harmonizes measurement procedures so that field strength and pfd data can be exchanged between administrations.

As a measure of precaution field strength or pfd measurements must in some cases be complemented by other measurements of the signal quality such as FM-to-AM conversion in propagation of FM transmissions, BER and channel impulse response (CIR) for digital mobile communication systems due to multipath transmission.

5.4.1.1 Quantities and units of measurement

5.4.1.1.1 Measurement conditions

The area surrounding a transmit antenna is usually divided into three regions:

1. Reactive near-field region.
2. Radiating near-field region (Fresnel).
3. Far-field region (Fraunhofer).

The reactive near-field region is defined as “that portion of the near-field region immediately surrounding the antenna wherein the reactive field dominates”.

The radiating near-field region is defined as “that region of the field of an antenna between the reactive near-field region and the far-field region wherein radiation fields predominate and wherein the angular field distribution is dependent upon the distance from the antenna”.

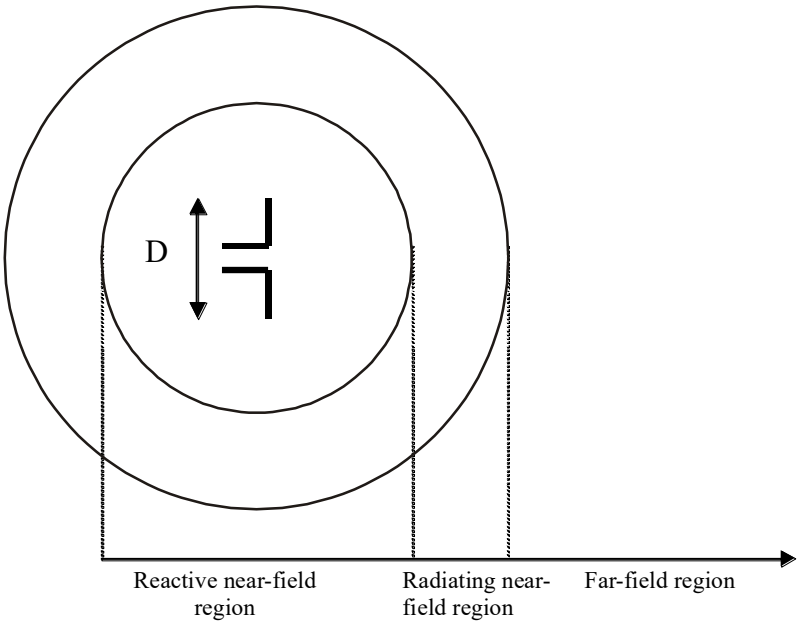
The far-field region is defined as “that region of the field of an antenna where the angular field distribution is essentially independent of the distance from the antenna”.

Antenna parameters provided by manufacturers are available in this region and the ratio E over H is equal to 377 Ω. This value can also be expressed as $120 \cdot \pi\ \Omega$.

Figure 5-21 shows how limits of each region might be defined.

FIGURE 5-21

Definition of field regions



Spectrum-4.4-01

Table 5-4 provides some values to determine boundaries between each region.

5.4.1.1.2 Electric and magnetic field strength

The unit of measurement of field strength commonly used is (V/m) and decimal sub-multiples thereof.

This unit is rigorously only applicable to the electric component (*E*) of the field but is generally also used for expressing measurements of magnetic field strength or the magnetic components of radiated fields by relation to the propagation impedance, usually free space (377 Ω) in which case the magnetic field strength (*H*) (A/m) in the far-field is given by:

$$H = \frac{E}{377\ \Omega} \tag{5-11}$$

TABLE 5-4

Definition of field regions

Region	Reactive near field region	Radiating near field region	Far field region
Region edges, measured from antenna, where: λ: wavelength D: largest dimension of the antenna	$0 \ldots \max. \begin{pmatrix} \lambda \\ D \\ \frac{D^2}{4\lambda} \end{pmatrix}$	$\max. \begin{pmatrix} \lambda \\ D \\ \frac{D^2}{4\lambda} \end{pmatrix} \ldots \max. \begin{pmatrix} 5\lambda \\ 5D \\ \frac{0.6D^2}{\lambda} \end{pmatrix}$	$\max. \begin{pmatrix} 5\lambda \\ 5D \\ \frac{0.6D^2}{\lambda} \end{pmatrix} \ldots \infty$
$E \perp H$	No	Effectively yes	Yes
$\eta = E/H$	$\neq \eta_0$	$\approx \eta_0$	$= \eta_0$
Component to be measured	E and H	E or H	E or H

For radiation or far-fields in free space the energies in the two fields are equal (for the definitions of near-and far-field, see Kraus [1950]). The type of antenna selected should be appropriate for the particular signals

involved. If the bandwidth of the emission being measured is broader than the bandwidth of the field strength equipment, consideration must be given to the degree to which the limited bandwidth of the field strength meter affects the reading of the actual field strength of the intercepted signal.

Field strengths are measured using antennas with known antenna factors. The electric antenna factor K_e of a receiving antenna is the electric field strength E of a plane wave divided by the output voltage V_o of the antenna at its nominal load resistance (which is normally 50 Ω).

$$K_e = E/V_0 \qquad 1/\text{m} \tag{5-12}$$

Reciprocally, the magnetic antenna factor for a loop antenna is the magnetic field strength H of a plane wave divided by the output voltage V_0 of the antenna at its nominal load resistance (usually 50 Ω).

$$K_h = H/V_0 \qquad \text{A/(m·V)} \tag{5-13}$$

The relation between the electric and the magnetic antenna factor in far-field and free space is given by:

$$K_e = 120\pi \cdot K_h \qquad 1/\text{m} \tag{5-14}$$

$$k_e = k_h + 51.5\ \text{dB} \qquad \text{dB/(m)} \tag{5-14bis}$$

Frequently, instead of the antenna factor, the gain G of an antenna relative to the isotropic antenna is given. The relationship between the isotropic gain G and the antenna factor K_e is derived by:

$$K_e = \frac{1}{\lambda\sqrt{G}} \cdot \sqrt{\frac{4\pi Z_0}{R_N}} = \frac{9.73}{\lambda\sqrt{G}} = \frac{f/\text{MHz}}{30.81\sqrt{G}} \tag{5-15}$$

where:

$Z_0 = 377\ \Omega = 120\pi\Omega$; the impedance of free space, and

$R_N = 50\ \Omega$, the nominal receiver input impedance.

Since voltage and field strength values are typically expressed as levels in dB(μV) and dB(μV/m) the antenna factors are also used in their logarithmic form:

where:

$$k_e = 20\log(K_e) \quad \text{and} \quad g = 10\log(G)$$

the antenna factor k_e is given in dB/(m) as:

$$k_e = -29.77\ \text{dB} - g + 20\log(f/MHz) \tag{5-16}$$

and so the level of the field strength e can be measured from the antenna output voltage level v_o using:

$$e(\text{dB}(\mu\text{V/m}) = v_o\big(\text{dB}(\mu\text{V})\big) + k_e(\text{dB/(m)}) \tag{5-17}$$

Since k_e normally does not contain the attenuation a_c of the transmission cable between antenna and measuring receiver, the equation has to be extended to (v_o being now the voltage at the input of the measuring receiver):

$$e(dB(\mu V/m) = v_o\big(dB(\mu V)\big) + k_e(dB/(m)) + a_c(dB) \tag{5-18}$$

Example: At the frequency of 100 MHz, an antenna with a gain of 6.5 dB has an antenna factor k_e of 3.7 dB. An input voltage v_o of 33.4 dB(μV) and a cable attenuation a_c of 1.1 dB corresponds to a field strength e of 38.2 dB(μV/m).

5.4.1.1.3 Equivalent incident field strength

The voltages measured at the input of a receiver can be expressed in terms of the corresponding voltages induced into the receiving antenna and hence the associated field strengths.

In the case of simple antennas e.g. vertical rod or loop, which respond only to waves from a single polarisation direction e.g. vertical or horizontal, it is convenient to introduce the concept of equivalent-incident field strength. This term is especially used in the HF range. It refers to the resultant field with the same polarisation as that to which the antenna responds. For any signal, it can be regarded as the sum of the sky wave and the ground reflected wave.

Commercial portable field strength meters and fixed installations using short vertical or loop antennas are normally calibrated in terms of equivalent-incident field strength. However, it should be noted that the concept of equivalent-incident field strength has little physical significance when used with extended antennas with limbs in different directions e.g. rhombic or with off-axis reception when using dipole on loop antennas.

The relationship between equivalent-incident field strength and the voltage induced in the receiving antenna is a function of frequency, and unlike the corresponding relationship for r.m.s. sky-wave field strength, it is independent of wave-arrival direction and ground constants.

Equivalent-incident field strength is therefore a more suitable parameter to use when comparing the results of measurements made at different locations and by different equipment. The use of r.m.s. sky-wave field strength would require a knowledge of the prevailing wave-field components, polarisations and arrival angles; in addition to an exact knowledge of the antenna pattern (see Recommendation ITU-R P.845).

5.4.1.1.4 Median available receiver power

The recommended ITU-R prediction method (Recommendation ITU-R P.533) for estimating sky-wave signal intensities gives values expressed in field strength or median available receiver power in the absence of receiving-system losses. The preferred signal-intensity parameter for the purpose of comparing predicted and measured results is the median available receiver power as it is independent of wave-arrival directions and polarisation (see Recommendation ITU-R P.845).

5.4.1.1.5 Power flux-density

At higher frequencies, especially above 1 GHz, measurement in terms of power flux-density (short: pfd, symbol: S) will in many cases provide more conventional information concerning the effective strength of the emission. The unit of pfd is W/m^2.

The power flux-density for a linearly polarized wave in free space is given by $S = E^2/Z_0$

where:

E : the field strength (V/m)

Z_0 : the impedance value of free space, 377 Ω.

The definition of the effective area, A_e for the measurement of the pfd is as follows:

With P being the received power (W), S being the pfd (W/m^2) and G being the isotropic antenna gain, the effective area A_e is (using the wavelength $\lambda = c/f$ with c as speed of light as $3 \cdot 10^8$ m/s):

$$A_e = P/S = \frac{\lambda^2 G}{4\pi} = \frac{\lambda^2 G}{12.57} = \frac{(84.62\ m)^2}{\left(f/_{\mathrm{MHz}}\right)^2} G \qquad (5\text{-}19)$$

where:

$$S = P/A_e$$

Using $p = 10 \log P$, $g = 10 \log G$ and $s = 10 \log S$, the effective area a_e in logarithmic quantities, dB(m^2) is:

$$a_e(\mathrm{dB(m^2)}) = 38.55 + g - 20 \log (f/\mathrm{MHz})$$

Thus $s(\mathrm{dB(W/m^2)}) = p(\mathrm{dB(W)}) - a_e(\mathrm{dB(m^2)})$.

If the received power p is given in dBm, the pfd s dB(W/m^2) may be derived using:

$$s(\mathrm{dB(W/m^2)}) = p(\mathrm{dBm}) - a_e(\mathrm{dB(m^2)}) - 30\ \mathrm{dB}$$

Since a_e normally does not contain the attenuation a_c of the transmission cable between antenna and measuring receiver, the equation has to be extended to:

$$s(\mathrm{dB(W/m^2)}) = p(\mathrm{dBm}) - a_e(\mathrm{dB(m^2)}) - 30\ \mathrm{dB} + a_c(\mathrm{dB}) \qquad (5\text{-}20)$$

Example: An antenna has a gain g of 15 dB at 1 GHz, then the effective area a_e is −6.45 dB(m^2). With a received power of −73.6 dBm and a cable attenuation of 3.5 dB, the pfd (s) will be −106.6 dB(W/m^2) or +13.4 dB(pW/m^2).

NOTE – Sometimes it is useful to calculate the effective area from a given antenna factor or vice versa. For that purpose, the following equations are given (with the quantities as defined above):

$$A_e = \frac{1}{K_e^2}\frac{Z_0}{R_N} \tag{5-21}$$

The effective area can also be expressed in logarithmic form:

$$a_e\big(dB(m^2)\big) = 8.77\ dB - k_e(dB/(m)) \tag{5-22}$$

5.4.1.2 Division into frequency ranges

It is sometimes convenient to classify techniques for the measurement of field strength and pfd into three frequency ranges:

– below about 30 MHz;

– between about 30 and 1 000 MHz;

– above about 1 GHz.

This division is useful because the optimum technique differs for these ranges. This results to some extent from the relationship between the dimensions of practical antennas and the wavelengths of signals to be measured, and also from the proximity effects of the terrain, which affects measurements in different respects in the three ranges. Below about 30 MHz (wavelengths longer than about 10 m), practical antennas are usually small (0.1 λ) compared to the wavelength. The most common measuring antenna is a loop of one or more electrically shielded turns, with a diameter of the order of 0.6 m, or a vertical rod antenna the length of which is short compared to one-quarter of the wavelength. These antennas may be either active or passive. If an active antenna is used care must be taken to avoid overload. The vertical rod antenna is used with counter poise on the Earth. The rod antenna has the advantage of being omnidirectional.

Below roughly 30 MHz it is usually necessary to measure field strength at heights electrically near the Earth. The characteristics of the ground and nearby vegetation, wires, and structures affect differently the strength of the electric and magnetic components of the field and the angle of polarisation. They may also influence the antenna impedance. Measurements using electrically shielded loop antennas are usually influenced by nearby objects to a considerably smaller degree than those using rod antennas.

From about 30 to 1 000 MHz (wavelength from about 10 m to 30 cm), practical antennas have dimensions, which are comparable to the wavelength. For a fixed frequency in this range the antenna most commonly used for field strength measurements is a half-wavelength resonant dipole. The dipole is connected to the measuring instrument by means of a balanced-to-unbalanced transformer (balun) and a coaxial transmission line. The resonant dipole antenna differs from the loop and short rod-antenna in that it is highly efficient (loss resistance very low relative to radiation resistance). With dipole antennas care must be taken to avoid (or reduce) mutual coupling with the environment and the antenna cable as a source of uncertainty. Broadband antennas or directional antennas are frequently used in the upper portion of this frequency range, particularly the log-periodic and conical-log-spiral type. Directivity will normally avoid or reduce mutual coupling with the environment.

Above about 1 GHz (wavelength smaller than about 30 cm), the aperture area of the dipole becomes too small to provide the necessary sensitivity. At these frequencies, it is the normal practice to employ antennas that collect energy from apertures that are large in relation to the wavelength, e.g., horns and parabolic reflector systems. These antennas are usually characterized by high efficiency (in excess of 50%) and appreciable directivity. Coaxial or waveguide transmission lines are employed.

5.4.2 Choice of measurement sites

As described above, the field strength at a receiving site depends on space and time. Therefore, measurements of field strength with an antenna at a fixed location (fixed position on the ground, fixed direction and height) can only show the time dependence of field strength.

5.4.2.1 Fixed installations

As far as possible, a site should be selected where the fields of the emissions to be recorded will be relatively undisturbed by local structures or terrain features. Nearby overhead conductors, buildings, large trees, other

antennas and masts, hills and other man-made and natural features may seriously distort or disturb the wave front of the emission. The degree to which these conditions limit the validity of the measurements depends on a number of factors including the frequency range and the type and orientation of the antenna used with the field strength measurement equipment. At frequencies in the HF and lower ranges, it is common practice to use vertical monopole antennas or broadband arrays with essentially vertical polarisation reception characteristics and in some instances e.g. at the top of buildings vertical or horizontal dipoles which however must be used with caution in view of calibration difficulties. Such antennas are especially vulnerable to overhead conductors and structures.

At the higher frequencies, where highly directional antennas are used, it is important that the path in the general direction of the signal source be clear; additionally multiple-path reception due to local reflection or re-radiation of the wanted signal must be minimized. Where an antenna with a high front-to-back gain ratio is used (e.g., antennas mounted in parabolic or corner reflectors) reflection or re-radiation sources behind the array are not so likely to cause trouble as with antennas having more limited directional characteristics.

Fixed sites are primarily used for measurements below about 30 MHz. For that purpose, the following criteria are suggested:

– the immediate vicinity of the site should consist of level terrain situated in a relatively level area;
– for ground level vertical monopole antennas soil with relatively high conductivity and free of gravel or outcroppings of rock is desirable;
– there should preferably be no overhead conductors (e.g., antennas, power and telephone lines or metal roofed or guttered buildings) within 100 m of the antenna site. At the lower frequencies, where 100 m represents one-half wavelength or less, at the operating frequency, it is desirable that overhead conductors be 20 m or more removed from the receiving antenna for every 1 m of height above ground of the overhead conductor, out to a distance equal to at least one-half wavelength.

5.4.2.2 Mobile installations

Mobile installations i.e. field strength measuring equipment in a monitoring vehicle, have the following advantages over fixed installations: they can be used in stationary applications when the vehicle is not moving and in mobile application and can thus be used to observe both space and time distribution of field strength.

5.4.2.2.1 Stationary application

In many cases field strength measurements on several points but with variable height of the measuring antenna are the preferred solution in order to find the expected value of field strength especially in the VHF/UHF range. This can be achieved by moving the vehicle from point-to-point and by measuring the field strength on the frequencies of interest at different heights. The antenna is mounted on top of a telescopic support attached to the vehicle at a height normally 10 m above ground. In view of the propagation characteristics in these bands, the antenna has to be adjusted to the direction and polarisation of the received signal.

5.4.2.2.2 Measurements with a portable field strength meter

Measurements with a portable field strength meter are done manually with the antenna close to the person reading the field strength values. Rod antennas must however be positioned on the ground. In general, the same desirable site criteria apply as for fixed installations except that somewhat greater latitude can be allowed provided that the “cluster measurement” technique is used. This technique involves making several separate measurements with the antenna at a slightly different location for each measurement (of the order of one to five metres separation depending on the frequency, with the larger value applicable to the lower frequencies). The result is a cluster or group of measurements around a central point. The individual measurement values are then averaged to arrive at a final value. In measurements using a shielded loop antenna, a few measurements will usually suffice since this type of antenna, which is responsive to the magnetic component of the wave, is usually less affected by locally disturbed conditions (reflection and re-radiation effects) than is the case with rod or dipole antennas. If the field strength meter utilises a loop or other directional antenna and if the approximate azimuth of the station being measured is known with respect to the measuring site, the presence of local disturbances can often be detected by adjusting the antenna for maximum signal pick-up and noting whether the indicated direction of arrival is in agreement with the actual direction of the station. Where the indicated and true directions differ appreciably it would be well to select a different site for the measurement.

For measurements in the VHF and higher ranges it may be found that an undisturbed site cannot be located, in which case the cluster technique involving ten or more consistent individual measurements may be required to arrive at reasonably accurate results.

Considering measurement carried out by such standalone equipment, the influence of quick motion of the equipment and the vicinity of the user may influence and may lead to a mistaken result. So, for a good measurement, this type of equipment should be installed on a tripod to carry out the measurement.

For HF sky-wave signals, the use of the "cluster technique" may be replaced by time-averaged measurements at a single location.

5.4.3 Methods of measurement

Many methods of performing field strength measurements at monitoring stations may be used depending on the information desired, including:

– continuous recording over extended periods (in obtaining propagation information with respect to seasonal and sunspot cycle variations, data have been collected over particular paths in the MF broadcast band covering approximately 30 years);

– continuous recording over shorter periods to determine day-night or other short-term variations in signal level;

– sampling at short intervals (for example, for 5 s every 2 min);

– sampling at longer intervals (for example, for 10 min each 90 min).

In some instances, especially where a ground wave is being observed, a single short period of measurement may suffice, depending upon the purpose for which the measurement is required. In certain cases, e.g. measurements for the purpose of HF propagation studies, one may require information concerning the overall propagation conditions over a band of frequencies.

Therefore, it may be expedient to make short records lasting about 10 min, over the entire high-frequency band at intervals of about 90 min of stations known to be working 24 h a day, so chosen that the ranges of frequencies and distances of interest are well represented. In the case of sky-wave signals, it may also be necessary to take measurements on different days to take account of day-to-day variations in the ionosphere.

Recommendation ITU-R SM.378 recommends that, except where there are limitations due to the receiver noise-level, atmospheric noise or external interference, the accuracy to be expected in field strength measurements should be better than ±2 dB for frequencies below 30 MHz and ±3 dB for frequencies above 30 MHz.

Microprocessor controlled equipment can switch frequencies, switch antennas if appropriate, discharge receiver pass-band residual energy, measure on a new frequency including applying correction factors, and digitally record results within a period of a few tens of milliseconds. This type of system is useful when a number of frequencies need to be measured or when long-term sampling will produce too much data to manually store and analyse. The results are, of course, stored in a computer because of the great amount of data collected in a short time.

5.4.3.1 Measurements at a fixed measuring point

5.4.3.1.1 Instantaneous measurements

At a given measurement point located at a given distance from the transmitter samples of the distribution of field strength can be taken. At the required height the antenna should be turned in the direction of the transmitter. During the measurement period the height and orientation of the antenna should be varied to read and record the maximum field strength.

5.4.3.1.2 Short-time and long-time measurements

To measure the time distribution of field strength, a permanently installed system e.g. at a fixed station or a containerized station, short- or long-time measurements can be executed. The measurements can be continuous or repeated at regular intervals permitting the observation of several frequencies. A measuring program executed according to a plan provides adequate results to determine propagation properties, varying by the

time of the day or the seasons or the sun spots. Very long-time measurements require short regular calibration checks. Long-time measurements are also possible using manual measuring equipment together with a data recorder.

5.4.3.1.3 Measuring the spatial-distribution of the field strength

For high reliability estimation of the expected field strength at a point at a given distance from a transmitter, one should know the spatial distribution of the field strength in the environment local to the point of measurement. To that end measurements should be taken at several points on a demarcated area. Based on a normal distribution the required number of samples, for a certain degree of reliability, that the field strength lies within a certain range of values around the expected field strength, depends on the standard deviation σ. By finding the best and worst reception points of that area E_{max} and E_{min} can be measured. Based on practical experience an estimate of the standard deviation can be obtained using: $E_{max} - E_{min} = 5\sigma$.

The required number of samples can be determined from Table 5-5 (*D* is the achieved accuracy):

TABLE 5-5

Required number of samples depending on $E_{max} - E_{min}$

		$E_{max} - E_{min}$ (dB)			
Confidence level (%)	***D*** **(±dB)**	**0 to 5**	**5 to 10**	**10 to 15**	**15 to 20**
90	1	3	11	24	43
90	1.5	2	5	11	19
95	1	4	15	35	61
95	1.5	2	7	15	27

5.4.3.2 Measurements along a route

Influenced by the local receiving conditions, the real values of the field strength can significantly differ from their predicted values. Therefore, they must be checked by measurements for establishing the radio field strength coverage of a large area.

The test results must be recorded along with their geographical coordinate data for locating the scenes of measurements and for mapping the results that were gathered on the most accessible roads of the area in question.

Instead of measuring the actual field strength, there is sometimes the necessity for measuring the output voltage of a user antenna (the typical antenna for the service under investigation) for radio coverage evaluation.

Digital network systems (such as LTE, DVB-T, or DAB) are sensitive to the effects of reflected reception. In this case, besides measuring the field strength, the reception quality measurement, made by the measurement of the bit-error ratio (BER) or channel impulse response (CIR), it is also necessary to determine the system performance evaluation. Using automatically made calls, these measurements can be made in cellular phone networks without affecting normal operation.

For measurement purposes along a route a continuous transmission is necessary. Further information can be found, e.g., in Recommendation ITU-R SM.1708.

5.4.3.2.1 Results of mobile field strength measurement

Due to the effect of reflected signals, the field strength along a route shows severe fluctuation. The result of a single measurement can coincide with the minimum or maximum value of reflection and is also influenced by the chosen height of the receiver antenna, the season, the weather, the vegetation and the wetness of surroundings.

Considering the factors mentioned above, reproducible field strength test results can be calculated from a large number of raw data readings, by means of statistical processing of them.

5.4.3.2.2 Necessary number of measuring points and the averaging interval

For statistical evaluation ('Lee method', see [Lee1986]) the number of sample points should be chosen in such a way that the results should display the process of slow changing in the field strength (effect of long-term fading) and, more or less, they should also reflect the local (instantaneous) individuality (effect of short-term fading) of the field strength distribution.

For that, a sliding average window is applied to the recorded values. The choice of interval length depends on the desired stability of values. Typical values can be found in Table 5-6, which can be read as follows: for obtaining 1 dB confidence interval around the real mean value, the samples of test points should be chosen at each 0.8 λ (wavelength), over 40 λ averaging interval (50 measured values within 40 λ). Please note that longer averaging intervals will smooth out the local mean, which is not desired.

TABLE 5-6

Required number of samples for mobile measurements for certain confidence intervals

Averaging interval in terms of wavelength (n·λ)	Standard Deviation σ	Field strength spread in dB
5	0.165	3
10	0.122	2.1
20	0.09	1.56
40	0.06	1

Please note that this method implies the use of an instrument that has a certain measurement time. In case high-speed digitizers are used or if the level is determined right away from the I/Q samples, some additional aspects are to be taken of. Further reading can be found in [MOB_VOLTAGE].

5.4.3.2.3 Velocity of the vehicle

The velocity of the vehicle must be appropriate for the wavelength (taking into account the Lee method, see above), the simultaneously measured number of the tested signals with different frequencies and the applicable shortest measuring time of the test receiver.

$$v = \frac{864}{f/_{\mathrm{MHz}} \cdot t_r/_{\mathrm{s}}} \mathrm{km/h} \tag{5-23}$$

where t_r is the minimum time given by the receiver specifications to revisit a single frequency.

5.4.3.2.4 Measuring antennas

During the measurement the chosen height of the test antenna is 1.5-3 m. The result will be considered as being carried out at a height of 3 m.

The received signal comes from different angles to the test antenna, therefore the effect of the antenna diagram on the field strength test result should be known.

The antenna factor (*k*) accuracy should be within 1 dB.

The deviation of the horizontal radiation diagram of the measuring antenna from a non-directional diagram should not exceed 3 dB.

5.4.3.2.5 Navigation and positioning systems

Dead Reckoning System

The distance from the starting point is reckoned with the help of a distance-to-pulse transducer attached to a non-motor driven wheel of the test vehicle, while the mechanical gyroscope provides the heading information. The location accuracy depends on the accuracy of the starting point registration and the distance covered by the test vehicle.

GNSS

The spatial resolution of today's GNSS along with modern receivers is easily within a few meters. Detailed information on the matter can be found in § 7.1.

Complex Navigation System

This system is the combination of the above-mentioned systems. Without the need for manual operator intervention, these navigation systems continuously provide position and time data, heading and waypoint information. Depending on the task, a combination of distance-to-pulse transducer (instead of a full dead-reckoning system) combined with a GNSS receiver might suffice.

5.4.3.2.6 Measurement result collecting with data reduction

By means of statistical processing, this method allows the amount of registered raw data to be reduced considerably.

Averaged values

Some of the test receivers are able to perform internal classification of test results over predefined user intervals. The user can select the evaluation intervals of up to some 10 000 measured samples, but each interval must contain at least 100 values.

Only the arithmetic averaged values of the predefined number of test results are stored and are indicated on the final map of radio coverage.

Classification of results according to level exceeding probability

During measurements the results are classified according to exceeding probability, between 1 and 99%. These percentage values represent the probability of overstepping for the applicable field strength level. Their typical values are 1; 10; 50; 90 and 99%. The median value, 50% is preferred for propagation studies.

It deserves attention that receivers require some very short time (milliseconds) for that classification. During that time, trigger pulses might be ignored, therefore no new measurements are obtained.

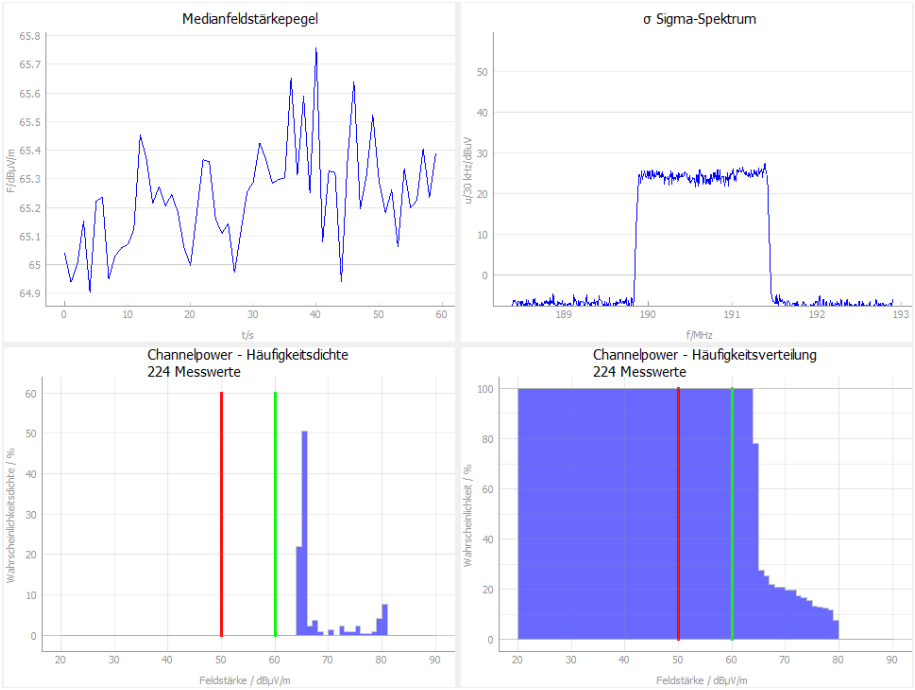
5.4.3.2.7 Data presentation

The data presentation leans itself by the desired use of the measurement data and if the measurement is currently running or if the measurement data is evaluated and prepared for reports.

If the measurements are currently running, then the engineers predominantly require a way to monitor the health of the data acquisition system. This can be aided by some navigational aids, like digital maps to guide the monitoring vehicle's driver. In some cases, the field strength probability distribution may support the measurement team by indicating an optical guide regarding the uniformity / normality of the local field strength distribution, as shown in Fig. 5-22.

FIGURE 5-22

Data presentation on a mobile field strength recorder:
field strength vs. time and spectrum in the upper half; field strength probability density and cumulated probability distribution with marker lines indicating limits for coverage studies



If the measurement was done to study certain propagation related effects, diagrams related to usual statistical methods like histograms or probability density functions are of major interest. If the measurement was done to check coverage obligations, digital maps in various forms are the key to a dynamic result presentation.

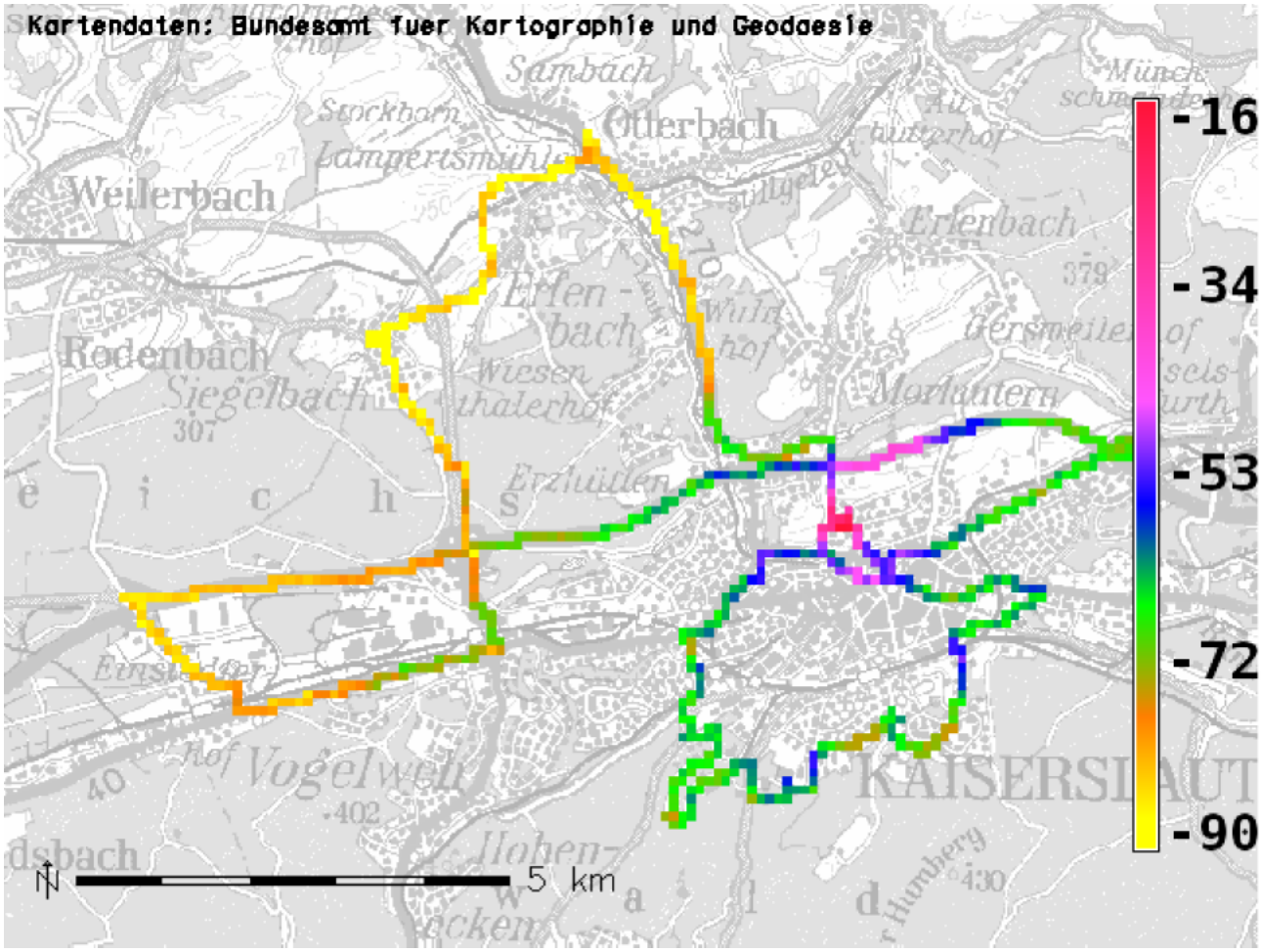
Nonetheless, as all the work is done on a computer, the term ‘presentation’ and ‘storage’ are separate matters. More information on the subject of data storage and presentation can be found in Chapter 4.

It should be evident that presentation of raw data in tabular form doesn’t give that much information. For that, at least an easy way of presenting time series data with the option to pan and zoom allows to examine the data and show local fading effects.

In digital mapping applications, a multicoloured line can represent the raw or processed field strength levels (e.g. with 10 dB(µV/m) scale) or the level exceeding probabilities (between 1 and 99%). An example can be found in Fig. 5-23.

FIGURE 5-23

Example of color-coded representation of median receiver input levels along a route



The scale of the selected map should correspond to the size of the area covered by the radio signal under investigation and the required resolution of processed field strength results. Due to the scale of the map, the represented intervals can include the multiples of the averaged intervals. The resolution of the presented result should be chosen in such a way that it can plot local peculiarities without the coloured line being too colourful.

If there is a need to represent the averaged intervals with higher resolution (e.g. when representing results in microcells), the system should allow to zoom into the map.

If during the measurements two data series are registered simultaneously (e.g. field strength and BER) it is expedient to represent them together, by two parallel coloured lines along the plotted roads of the map (see § 7.2 for more details about maps) or to interactively switch between those two presentation layers.

5.4.3.3 Comparison of measured and calculated data

The e.i.r.p. of the emitter is utilised to compute the coverage of the station.

The monitored data may be utilised:

– to estimate the e.i.r.p.;

– to evaluate and verify the propagation model and the digital terrain model.

The calculated data may be utilised:

– to estimate the amplitude calibration of the receiving system: antenna, cables, receiver;

– to evaluate the calibration.

5.4.3.3.1 Comparison of predicted and measured field strength in FM broadcasting

Radio signals vary over time and with small differences in location. This variability is incorporated into many propagation prediction methods. In most cases, monitoring measurements are made at one location and for a period of time that may be too small to fully define the time variability. As a result, measurements must be considered carefully when comparing them to predictions. The example here is for a situation where the variability may be small and comparisons can be made with confidence. But there are many cases where variance will be larger and comparisons must be made with careful consideration of the differences observed.

The Regional Agreement (Geneva, 1984) contains the planning bases of FM broadcast stations in Region 1. In this plan can be found which countries may use what frequencies with parameters such as power, antenna height, antenna diagram, polarisation etc. The Master International Frequency Register (MIFR) reflects the actual situation in the ITU bi-weekly BR IFIC DVD.

It is the task of national administrations, by means of their monitoring service, to check that these broadcast stations comply with the assigned parameters. This can be done by means of physical inspection of all stations on a regularly bases, for instance once every year (or two years). For time and cost saving, a monitoring system measures the broadcasting stations from one or more fixed monitoring stations and compares the results with the predicted values. If the results of this comparison indicate that the emitted power of the station is too high (or the antenna is mounted higher than permitted) a physical inspection can be carried out.

5.4.3.3.2 Planning software and databases

The frequency management often uses software to calculate the necessary parameters for their stations to be planned or check coordination requests from neighbouring countries. The planning software may also produce a so-called frequency scan. In this case, the programme scans the database containing information of the band 87.5 to 108.0 MHz and automatically generates a list for a given location containing all 204 channels with the predicted field strength of all the stations working on that frequency. The number of stations in this list with the calculated field strength on a certain frequency depends on the size of the database used and on a pre-defined level of field strength, which should be taken into account.

5.4.3.3.3 Predicted field strength from remote monitoring stations

As an example, a network of 12 remotely controlled stations is used in one country. For each location of these remote monitoring stations the planning tool can produce a list of predicted field strength values for all 204 FM broadcasting channels. Only the strongest station on each channel is needed. However, a more extended list is desirable because the station with the strongest calculated field strength may work with reduced power so another station might be received instead. Predictions for this example were made using the propagation model in superseded Recommendation ITU-R P.370. Future predictions may, for example, be made using Recommendation ITU-R P.1546.

5.4.3.3.4 Measured signal strength from remote monitoring stations

All remote monitoring stations consist of two receivers using the same antenna via a splitter. Receiver one scans the frequency band on all stations sequentially. The results are displayed in 12 windows on two 21-inch screens. The second receiver can be used to identify stations displayed on the screen as a result from the measurements of the first receiver. Every 10 s a scan is made of the whole band. The values of the measured signal strengths of all steps are stored after each scan. The system measures continuously for 24 h (but could also be less e.g. during day-time only). The channel separation in FM broadcasting in Region 1 is 100 kHz. So, for the processing of the values of the measured signal strengths in order to compare with the predicted field strength, only those on the exact channels (87.6 MHz, 87.7, 87.8, etc.) are needed. From every channel the median value over the measured 24 h is taken. In this way the effects of changing propagation during the day are minimized.

5.4.3.3.5 Comparison of predicted and measured values

For each of these 12 locations the predicted and the measured median values are available. These values can be compared with each other automatically and presented on a screen in portions of, for example, 23 channels (see Fig. 5-24).

The green bars (measured levels) change into red in case the measured value is equal to or exceeds the predicted value. From here it is possible to zoom in on the transmitter of interest. Detailed information with earlier measurements of the station of interest is available. It can be taken into consideration whether an inspection engineer is sent to (one or more) stations exceeding the predicted values. The described measurements should be repeated regularly, so it can be used to give additional information such as:

– produce presentations containing historical trends on each channel per location, graphically or in ordinary text;

– display the measured values over time in a distribution plot;

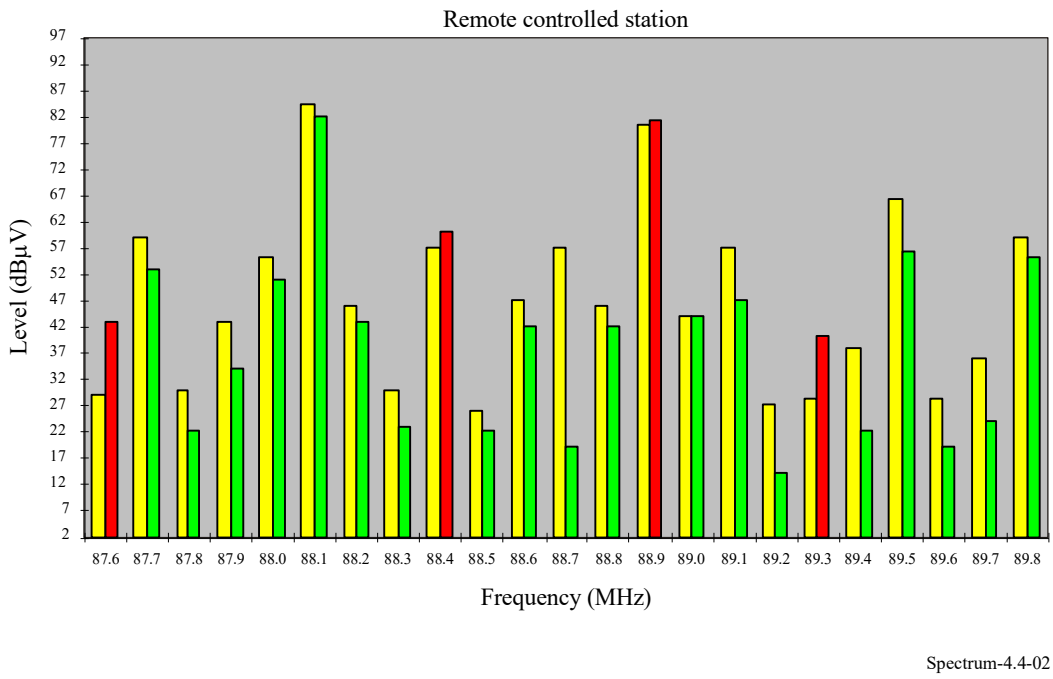
– calculate all the measured exceeding on each remote station;

– automatically detect unauthorised stations per measurement/station and produce overviews about the trends in illegal use. In this way, the effects of enforcement efforts can be presented;

– carry out checks on antenna diagrams of broadcasting station by comparing the predicted field strengths from one broadcast station measured from more than one (as many as possible) remote monitoring station from different directions.

FIGURE 5-24

Predicted (yellow) and measured (green or red) levels between 87.6 and 89.9 MHz from a remote monitoring station



5.4.4 Evaluation, processing and documentation of measurement results

5.4.4.1 Definition of statistical parameters of field strength and pfd

The method used in deriving data from recordings depends primarily upon the purpose for which the data will be used. In propagation studies, it is common practice to determine the signal level exceeded during a specified percentage of time, or the maximum or minimum value over a predetermined period of time; for example:

– the median value (the level exceeded 50% of the time);

– the 90% value;

– the 10% value;

– the highest signal level;

– the lowest signal level.

The median value (dB(µV/m)) is a desirable form of presentation of measurements at discrete frequencies for propagation studies. Although 60 min periods are widely used (at HF) as the basic period of time for the

analysis, shorter or longer periods (e.g., 1 min, 10 min or several hours) may be preferable in specific instances. At the lower frequencies, especially below 30 MHz, where there is a wide variation in signal level depending upon the time of day, such as occurs in the MF and HF broadcasting bands, analysis may be made over hourly periods centred on sunrise and sunset at the midpoint of the path between the transmitter and the receiver. Use of a computer for this purpose simplifies and speeds the analyses.

Frequently the level of field strength in dB(μV/m) shows Gaussian (normal) distribution both with time and space dependence. For other distributions, see Recommendation ITU-R P.1057.

The distribution of measured field strength values, when expressed in linear units (e.g. V/m, mV/m or μV/m), frequently follows a log-normal distribution. When these data are converted to dB, the distribution follows a normal (Gaussian) distribution, and different formulas are required. For the case of Gaussian distribution, the following definitions apply:

The corrected empirical variance of field strength is given by:

$$s^{*2} = \frac{n}{n-1} s^2 \quad \text{dB} \tag{5-24}$$

where:

n : number of samples

s^2 : empirical value.

$$s^2 = \sum_{i=1}^{n} (e_i - \bar{e})^2 \quad \text{dB} \tag{5-25}$$

where:

e_i : sampling value of field strength (dB(μV/m))

$\bar{e}$: arithmetic mean of samples (dB(μV/m)).

5.4.4.2 Evaluation of space and time dependency of field strength

In an area located at a distance L from the transmitter, where there is a sufficient number of samples, knowing the mean field strength (arithmetic mean $\bar{e}$ of samples) and the standard deviation by location σ_L, the distribution function $N(\bar{e},\sigma_L)$ can be derived. Adequately, during a relatively long period of time, where there is a sufficient number of samples, knowing the mean value of the field strength (arithmetic mean $\bar{e}$ of samples) and the standard deviation by time σ_t, the distribution function $N(\bar{e},\sigma_t)$ can be derived.

With the reduced value of standard deviation by location and variance by time, the distribution function $N(\bar{e}, \sigma_{L,t})$ be determined.

$$\sigma_{L,t} = \sqrt{\sigma_L^2 + \sigma_t^2} \quad \text{dB} \tag{5-26}$$

For further details, see Recommendations ITU-R P.1546 and ITU-R P.845.

5.4.4.3 Example checklist for coordination data

The European cooperation agreement [HCM] has among others stated the following measurement procedure in cases of disagreement concerning the results of evaluation related to a specific coordination request, to facilitate the enhancement of existing networks and in cases of harmful interference between stations in border regions in the VHF/UHF ranges. Results of field strength measurements shall be exchanged, and therefore the measurement procedures have been standardized.

Measurement sites shall be selected so that there are no reflecting objects or as few as possible within ten times the wavelength (10 λ). Visual contact with the transmitting antenna should exist where possible.

Depending on the conditions of measurement different records of the measurement including the setup must be made, so that the results are reproducible. The whole equipment shall be specified.

In cases of fixed point measurement, the height of the measurement antenna(s), measured from the ground, has to be varied between 3 and 10 m. Within this range the highest field strength value shall be recorded, as well as the height of the antenna where this value was measured. This value has to be regarded as being a field strength value at a height of 10 m.

A record of every measurement set-up and every measurement must be stored in a data base. All data relevant to explain the measurement results have to be recorded for later calculations.

Relevant measurement data (in cases of harmful interference):

Interfering assignment:

– Administration;
– frequency (MHz);
– supposed location or direction to interfered assignment;
– designation of emission;
– measured field strength (dB(μV/m)).

Interfered assignment:

– Administration reference number;
– frequency (MHz);
– location name;
– location coordinates (degrees/min/s);
– class of station.

Type of measurement:

– fixed point, number of points;
– measurement over longer time period;
– mobile.

Measurement data:

– Number of the measurement
– Measured frequency
– Measured bandwidth
– Date (DD/MM/YY)
– Time period (from/to) (HH/MM to HH/MM)
– Location name
– Geographical location (degrees/min/s)
– Location height (m above sea level)
– Height of measurement antenna (m above ground)
– Polarization of measurement antenna (h/v)
– Customer's antenna ☐ yes ☐ no
– Description of transmission path
– Propagation (weather) conditions
– Remarks (IF bandwidth, modulation, bit-error rate, if required).

Measurement results: (in case of measurements over a longer time period)

– Quasi-maximum value (10%): (dB(μV/m)).
– Quasi-minimum value (90%): (dB(μV/m)).
– Measured (Median) value: (dB(μV/m)).

5.4.5 Calibration of measuring instruments and antennas

Calibration of the field strength measuring apparatus normally includes the separate calibration of the measuring receiver and of the measuring antenna including the transmission cable.

Only in early examples of (manual) HF field strength meters was the antenna a part of the tuning circuit and included in the calibration procedure.

The frequency of calibration is dependent on the equipment being used and the environment where it is being used e.g. antenna recalibration may be required more frequently for mobile operation or for locations with seasonal changes in ground conductivity.

More details on calibration can be found in § 2.3.4.

5.4.5.1 Calibration of measuring receivers

The calibration of measuring receivers is described in § 5.3.12 and in § 2.3.4.

5.4.5.2 Calibration of the measuring antennas

The portion of the calibration factor, which is determined by the antenna system characteristics (i.e., gain, together with line and transformer losses) is called the antenna factor (see § 5.4.1.1.2). In general, the calibration factor varies with frequency. Calibration methods may be classified under three basic categories, standard field method, standard antenna method and standard distance or standard site method. All methods must deliver antenna factors valid for the free space under far field conditions. It is important that antennas be mounted for measurement so that the antenna characteristics are not influenced by the antenna masts, cables, other antennas or reflecting objects in the vicinity.

5.4.5.2.1 Standard field method (direct calibration)

The standard field method is the most basic calibration method. It is directly derived from the definition equation of the antenna factor. The antenna is exposed to an electromagnetic field, the strength of which is accurately known. The field strength may be determined by calculations based on the measured current in a transmitting antenna of known dimensions and current distribution. For practical reasons the application of this method is limited to the calibration of loop antennas, since for other antenna types other methods give more accurate results.

5.4.5.2.2 Indirect calibration of antennas

Direct calibration is usually not employed to calibrate instruments having short rod antennas, since it would be necessary to establish accurately known uniform fields within a large test area occupied by the instrument and its antenna. In this method, the calibration factor is calculated from the computed or measured characteristics of the antenna and measured instrument characteristics. The passive radiator is removed from the field strength measuring equipment and replaced by a calibrated standard signal generator having impedance substantially equal to that of the antenna. An appropriate artificial antenna is usually used to calibrate the remaining equipment (impedance matching device plus measuring receiver) as a radio-frequency voltmeter (or power meter) against the standard signal generator. An antenna factor is computed for each frequency from the dimensions and current distribution of the antenna, from consideration of the antenna as an aperture, or from the measured gain of the antenna. If a transmission cable is used, it may be convenient in some cases to consider it a part of the receiver and to connect the calibrating generator to it, thus avoiding the need for separately determining cable loss and making allowances for it. A field strength meter with a shielded loop antenna can be used to cross-check the rod antenna calibration in the undisturbed far field of a radio station.

5.4.5.2.3 Standard antenna method (substitution method)

In the standard antenna method, a plane wave of unknown field strength is measured using an antenna with an accurately known antenna factor (standard gain antenna, e.g. standard dipole), which is then replaced (substituted) by the antenna to be calibrated. From the difference of receiver input voltage levels the antenna factor in dB can be determined. The antenna factors of standard gain antennas themselves are either calculated from their dimensions and the measured properties of adapting elements (e.g. baluns) or determined using an accurate calibration procedure. Compared with the method described in § 5.4.5.2.4 the substitution method has the disadvantage that the error of the antenna factor contributes to the total error of the method. Further errors can result from the different shapes of the standard gain antenna and the antenna to be calibrated when the

field is not an ideal plane wave. Halfwave dipoles used as standard gain antennas have in addition the disadvantage that they have to be mechanically tuned at every new frequency.

5.4.5.2.4 Standard distance or standard site method

When the standard distance method is applied, the antenna calibration is reduced to a precise measurement of the attenuation between two identical antennas, whose result is compared with the calculated value of site attenuation. For the determination of the free-space antenna factor, if possible, a free-space calibration set-up shall be used, which delivers the most accurate results. In this case the two antennas shall be mounted such that reflections from surrounding objects can be neglected. This is normally possible for directive antennas. If free-space conditions cannot be established e.g. a reflection method can be used where the two antennas are mounted above a reflecting ground plane and the attenuation is compared to the theoretical value assuming addition of the direct and reflected wave at the location of the receiving antenna. This method has to be applied with great care since mutual coupling between antenna and ground plane can influence the antenna factor. Therefore, the distance between the antennas and between each antenna and ground plane must be great enough that effects of mutual coupling are negligible. Special attention has to be paid to the location of the phase centres of the antennas. This potential source of error can be eliminated by adequate consideration of the effect on the measured attenuation in the calculation of the site attenuation.

As far as the evaluation of the results of the standard distance method is concerned a distinction must be made between the two-antenna method and the three-antenna method. If only an attenuation measurement with two antennas is executed, only the sum of both antenna gains in dB can be truly determined. The antenna factor, which is to be calculated, can only be attributed to one antenna when the data of the other antenna are known in advance. This limitation can be avoided by application of the three-antenna method, where three attenuation measurements with three antennas combined to three cyclically exchanged pairs (a+b, b+c, c+a) are executed. By solving a set of equations with three unknown variables, the gain (and antenna factor or effective area) of each individual antenna can be determined.

5.4.5.2.5 Computation of antenna factor from dimensions and current distribution

The computation of an antenna factor is facilitated by the use of simple types of antenna. Thus, for example, a thin short vertical rod antenna (shorter than 0.1 wavelength) located over an extensive ground plane, is assumed to have a linear current distribution, making its effective length one-half its physical length. Its impedance can be simulated approximately by a series capacitor connected between the standard signal generator and the input of the measuring apparatus. A second example is the thin half-wave dipole antenna, with assumed sinusoidal current distribution, which is frequently used for calibration purposes. This antenna has a computed effective length of λ/π and a radiation resistance of 73.3 Ω in free space. A practical cylindrical dipole must be cut noticeably shorter than one-half wavelength to achieve resonance. Its radiation resistance and effective length are lower than the corresponding values for an infinitely thin antenna. These differences are due to the effect of the finite thickness on the current distribution. The directional pattern of a practical dipole, however, does not differ much from that of the theoretical thin dipole, and the conclusion from this observation is that its gain and available power remain very close to the values of the theoretical thin antenna. These considerations indicate that a practical dipole may be considered equivalent to the theoretical thin antenna, plus a transformer to account for the change in radiation resistance. The balun is an additional transformer, the use of which may introduce significant errors unless its impedance matching characteristics are optimised and its loss taken into account. Commercially available precision dipoles have additional attenuators to stabilise the load impedance of the dipole, which is of advantage for antenna calibration. The method of moments (MoM) [Harrington, 1968] computes the antenna factor when the dimensions of the antenna are known. Care must be taken to properly apply the MoM to this problem, and it is desirable to use a measured crosscheck whenever possible.

5.4.5.3 Calibration of fixed recording installations

To achieve the desirable accuracies given in Recommendation ITU-R SM.378, the initial calibration of these installations may be made by comparison against a calibrated field strength meter of known accuracy and under controlled conditions. Such a calibration will be valid only so long as all of the conditions under which the initial calibration was made remain unchanged. Therefore, significant changes in antennas, transmission lines, or impedance matching devices, or in the site itself (e.g. addition or removal of nearby antennas or other

overhead conductors or obstructions) will normally require recalibration of the facility. Additionally, periodic calibration checks (normally daily) should be made against the local calibration source (standard signal generator, noise generator or built-in calibration source). Local broadcast stations may be used with care as another calibration check. If measurements are to be made over an extended frequency range, a calibration curve may be prepared based on comparison measurements at frequent intervals within the frequency range of interest. When performing these comparisons, the monitoring station antenna and the field strength meter antenna should have the same polarisation (e.g. both antennas adjusted for reception of vertically-polarised emissions or both for horizontally-polarised emissions).

For measurements below 30 MHz, where a field strength meter with a shielded loop antenna is commonly used to calibrate a recording installation having a vertical monopole antenna, satisfactory results will normally be obtained with the field strength meter at a convenient level near the ground (e.g. 1 m or so). For frequencies above 30 MHz where dipoles or other resonant antennas are normally used and where the Earth does not play a major part in the propagation, it is desirable that the antenna of the field strength meter be installed at the same height as the recording antenna (usually about 10 m above the ground). To avoid interaction between the antenna of the field strength meter and the recording antenna, it may be desirable to remove the recording antenna temporarily and to place the antenna of the field strength meter at the same location to obtain the reference field strength; then the antenna of the field strength meter is removed and the recording antenna re-installed. This presupposes that the signal source which is being used is constant in level during the calibration procedure. If a signal of varying intensity must be used, simultaneous measurements should be made with the two antennas near one another but spaced sufficiently to cause a minimum of interaction between the two antennas.

5.4.6 Field strength measurement for e.i.r.p. determination in the VHF and UHF bands

5.4.6.1 Introduction

At one specific measurement point in an ideal environment, the received field strength is given by the sum of the direct ray and one single reflected ray. This sum determines a field strength that varies periodically with the height of the receiving antenna, reaching maximum and minimum values.

Their height and level depend on various parameters such as frequency, polarization, distance and altitude difference between transmitter and receiver antenna, soil permittivity and conductivity at the reflection. When the theoretical curve is plotted together with the measured curve, expressed in relative terms of the total field strength to the reflected field strength ($|\mathbf{E}|/|\mathbf{E_r}|$), it is possible to arrange the two curves by altering the soil parameters and the difference in height of the reception point with respect to the reflection point. Once the best possible match has been obtained, the value of the field strength associated with the direct ray is derived by statistical methods. If the shape of the measurement and theoretical ratio doesn't match with sufficient precision, the measuring point is discarded and another one needs to be tested. This method is particularly suitable for elevated transmitter sites, for which it is easier to find a wide flat terrain without obstacles between transmitter and receiver and when it is not possible to reach the first maximum in the operating range of the measurement vehicles extractable antenna mast. The methods described here are primarily suited for:

– antennas located on tall towers;

– antennas located on in mountainous areas;

– antennas of the mobile service in rural areas.

They are especially well-proven for broadcasting systems like VHF-FM, DAB and television. This method is additional to the max-min method described in [ECC_Rec(12)03].

Beyond the methods shown here, [ECC_Rec(12)03] gives more information on the topic for a wider range of frequencies and discusses additional methods of measurement.

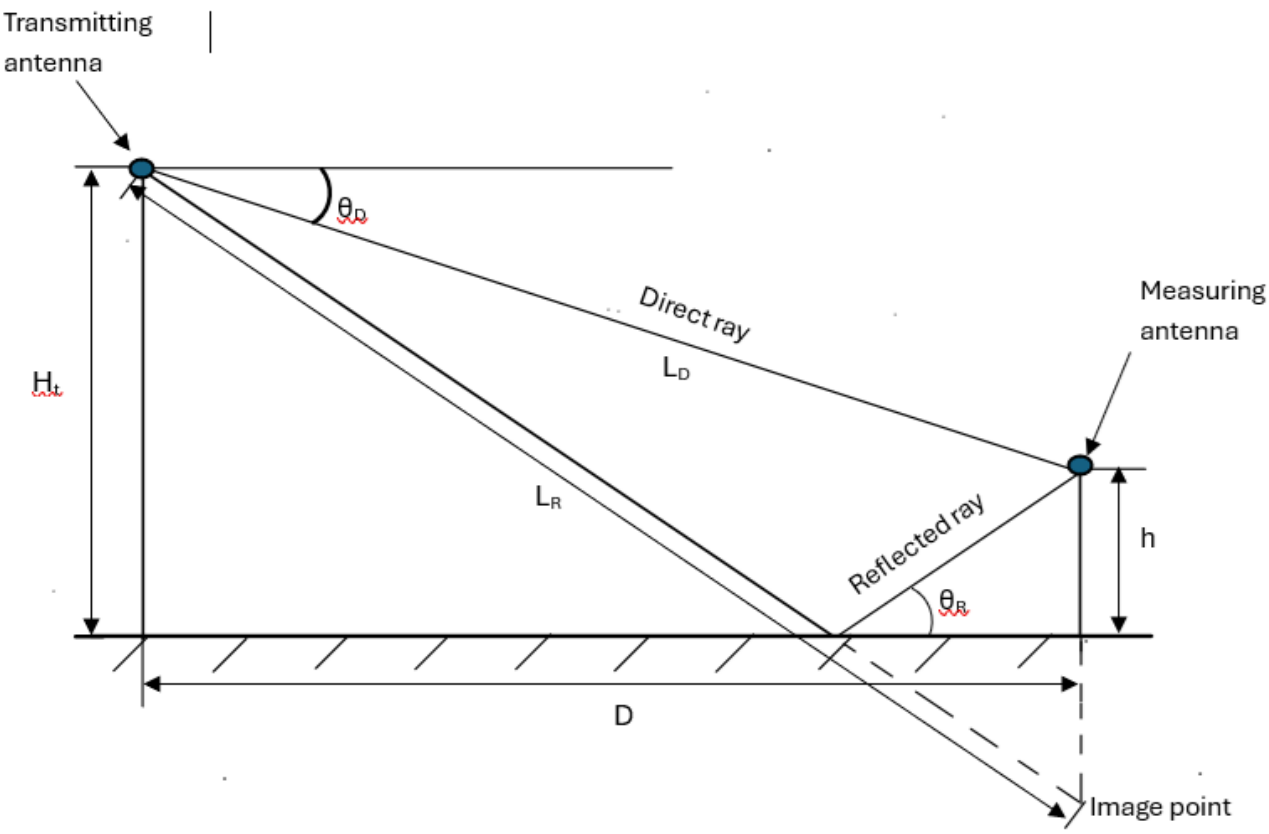
5.4.6.2 Theoretical description of the expected field strength at measurement points

In an ideal situation without clutter, the received field strength $\mathbf{E}$ is given by the vectorial sum of the field given by the direct ray $\mathbf{E_d}$ and the field of the reflected ray $\mathbf{E_r}$, taking into account polarization, the difference in the path length and the direction of arrival:

$$|\boldsymbol{E}| = |\boldsymbol{E_d}| + |\boldsymbol{E_r}| \tag{5-27}$$

FIGURE 5-25

Two-Ray model



For vertical polarization the electrical vectors of direct and reflected rays of **E** are coplanar to the plane of incidence. For horizontal polarization the vectors of the direct and reflected rays of **E** are orthogonal to the plane of incidence.

The reflected ray can be expressed by considering the magnitude and phase of the reflection coefficient. The reflection coefficient depends on:

– frequency respective wavelength λ;

– polarization;

– soil conductivity σ and relative permittivity ε_r of the ground at the point of reflection;

– angle of incidence (angle to the vertical axis $\psi = 90° - \vartheta_R$);

– θ_D and θ_R are the elevation angles of direct and reflected rays over the reflection surface;

– additional attenuation A due to different path length between direct and reflected ray Δr;.

– φ_r is the phase of the reflection coefficient at the angle of incidence Ψ;

– $\varphi_{\Delta r}$ is the phase difference between the direct and reflected ray.

Considering that, the field strength of the reflected ray can be expressed as:

$$E_r = E_d \cdot A \cdot |\Gamma(\varepsilon_r, \sigma, \psi)| \cdot e^{j(\varphi_\Gamma + \varphi_{\Delta r})} = E_d \cdot k \cdot e^{j(\varphi_\Gamma + \varphi_{\Delta r})} \quad (5\text{-}28)$$

with

$$k = A \cdot |\Gamma| \quad (5\text{-}29)$$

Some examples of values for the soil parameters are given in Table 5-7. Further guidance can be found in Recommendation ITU-R P.527 and [Gentile1966; Boithas1972].

TABLE 5-7

Typical soil parameters used for direct field strength measurements in Europe

Surface	Conductivity $\boldsymbol{\sigma}$ in mS/m	Relative Permittivity $\boldsymbol{\varepsilon_r}$
Dry soil	30	4
Rocky soil	1	4
Sea water	4000	80

The reflected ray for vertical polarization is more sensitive to the magnitude and phase of the reflection coefficient than for horizontal polarization. Experience shows that for horizontal polarization $|\Gamma|$ is close to 1 and the phase is close to π for quite every angle. This is different than vertical polarization, where the attenuation could be higher up to Brewster angle and the phase is larger than $-\pi$. Nonetheless, the properties of the soil have a rather negligible influence on the reflection coefficient in the VHF/UHF frequency range.

Additional attenuation and phase angle should be added for each receiving height in case of there are differences in the transmitting and receiving antenna patterns for the direct and the main reflected ray. According to [KAM1988], every time-variant propagation channel can be described by an equivalent two-way-channel with time-varying parameters for the reflection coefficient and time-delay. For that, the model used here is suitable for the described stationary reception scenario.

E, $\mathbf{E_d}$ and $\mathbf{E_r}$ are complex values. The ratio between the absolute value of the received signal |**E**| and the direct ray $|\mathbf{E_d}|$ is given by:

$$|R| = \frac{|E|}{|E_d|} = \frac{|E_d + E_r|}{|E_d|} \tag{5-30}$$

For horizontal and vertical polarization, the ratio |**R**| is given by

$$|R| = \sqrt{1 + k^2 + 2 \cdot k \cdot \cos(\varphi_\Gamma + \varphi\Delta r)} \tag{5-31}$$

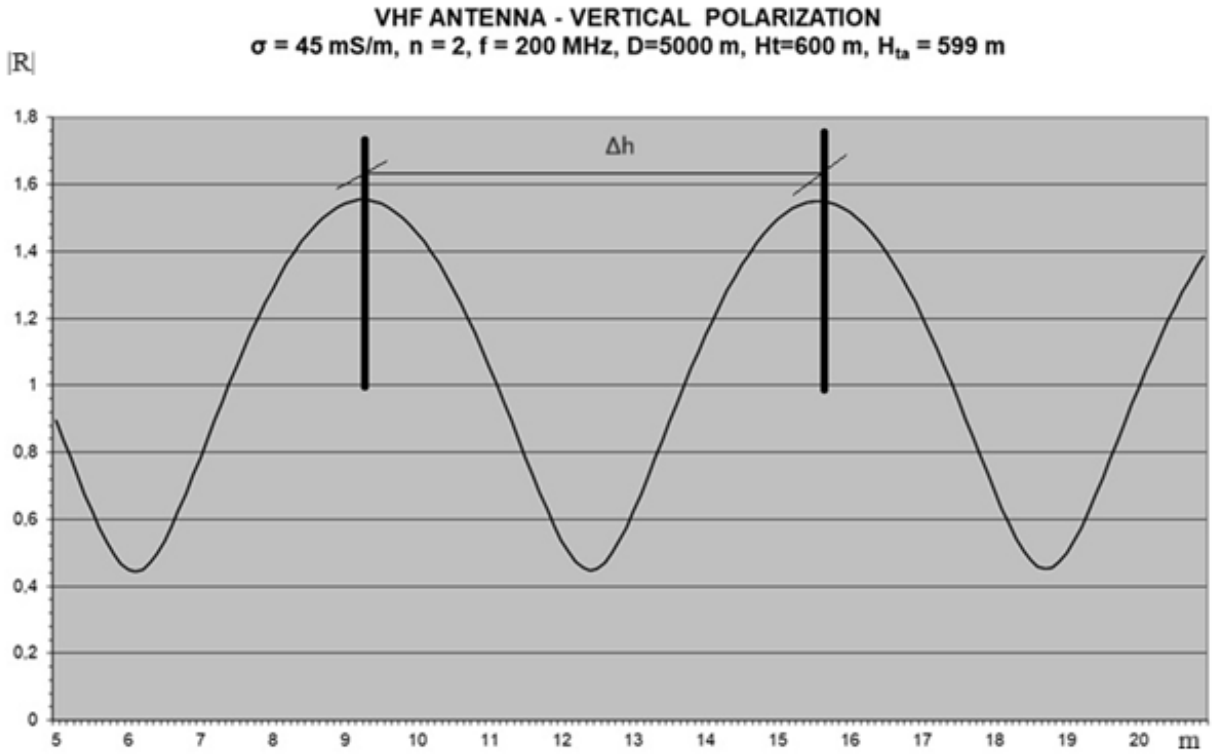
provided that for vertical polarization the angle Θ_D and Θ_R between, respectively $\mathbf{E_d}$ and $\mathbf{E_r}$, and the vertical axis is small, which leads to a cosine close to 1 in the equation above. It is because for vertical polarization the measured field strength is vertical.

|**R**| is a relative value in the range between 0 and 2. It varies continuously with the height of the measurement antenna.

A theoretical example of the shape of |**R**| is given in Fig. 5-26. The measurement height varies between 5 and 20 metres above the ground. The variation of the incidence angle due to the reception height is considered negligible due to the geometric relations. H_t is the height of the transmitting antenna with respect to reflection point. It takes into account the height of the ground and the height of the transmitting antenna.

FIGURE 5-26

Example of the ideal shape of $|R|$



For an ideal measuring point, the shape of the measured field strength with height should follow the theoretical one. In that case, the direct field strength is given by the measured values at the height for which |**R**| equals 1. If no measured values are available for that height, the value of |**R**| can be extrapolated from the available values.

5.4.6.3 Criteria for choosing measurement points

One of the main tasks in planning of measurements is to determine the height of the first maximum of the field strength and the minimum incremental step for the vertical scan. This determination allows to understand in which way measured and calculated values can be matched. Ideally, a measurement point should be chosen in a place where at least one maximum of the field strength falls within the extension range of the measurement vehicle's mast.

For VHF frequencies, the first maximum could be higher than the maximum height of the measuring mast, while for higher frequencies, it is easier to have more than one maximum and one minimum in the extension range of the receiving mast.

For horizontal polarization (index H) the height of the first maximum h_{Hmax} in metres is given by:

$$h_{Hmax} = \left|\frac{\lambda \cdot D}{4 \cdot H_{ta}}\right| \tag{5-32}$$

In equation (5-32), D is the distance between transmitter and receiver and H_{ta} is the adjusted height of the transmitting antenna with respect to reflection point. The adjustment accounts for the earth curvature and the vertical gradient of the propagation path of the atmosphere, is given by:

$$H_{ta} = H_t - \frac{D^2}{17} \tag{5-33}$$

with:

H_{ta}, H_t: corrected and measured height of transmitter above ground, in metres

D: distance between transmitting and receiving antenna, in kilometres

For vertical polarization (index V) the height of the first maximum is given by:

$$h_{Vmax} = \frac{\lambda \cdot D}{4 \cdot H_{e_t}} \cdot \frac{|\varphi \Gamma_v|}{\pi} \tag{5-34}$$

It should be noted that for vertical polarization the height of the first maximum is lower than for horizontal polarization.

The distance Δh between two consecutive maximum or minimum of the field strength is the double of the values given above for the corresponding polarization.

The incremental vertical Step S of mast should be 1/10 of the distance between two consecutive maximum or minimum.

$$S = \Delta h/10 \tag{5-35}$$

Given the frequency or frequency bands to be measured it is simple to observe that both S and h_{max} depend on the ratio D/H_{ta}.

Based on the constraint of having at least one maximum and at least one minimum in the vehicles mast range and the minimum incremental step available, the measurement distance D should fall in the range given by:

$$D \leq \frac{2 \cdot H_{ta}}{\lambda} \cdot h_{mast-ext} \tag{5-36}$$

$$D \geq \frac{20 \cdot H_{ta} \cdot S}{\lambda} \tag{5-37}$$

Therefore

$$\frac{20 \cdot H_{ta} \cdot S}{\lambda} \leq D \leq \frac{2 \cdot H_{ta}}{\lambda} \cdot h_{mast-ext} \tag{5-38}$$

Moreover, the measurement distance D in relation to antenna height H_{ta} determines the influence of the vertical antenna pattern in regards of the measured field strength.

5.4.6.4 Application of the methods

There are several ways based on the two-ray model to reach the result:

Method 1 – max-min method (log scale)

In this (simplest) case the "max-min method", in which both a maximum and a minimum can be detected during the measurement, the amplitude of the direct field strength E_d is given by the average of adjacent maximum and minimum measured values. The field strength of the direct wave is given by the median value between adjacent maximum and minimum measured values. If more than one pair of maximum and minimum measured values are available, the accuracy can be increased by calculating the average of these individual results for E_d..

$$E_d(mV/m) = (E_{max} + E_{min})/2 \tag{5-39}$$

or in logarithmic units:

$$E_d(dB\mu V/m) = E_{max}(dB\mu V/m) + n_k(dB) \tag{5-40}$$

with

$$n_k(dB) = 20 \cdot \log_{10}(1 + 10^{-\left(\frac{E_{max}(dB) - E_{min}(dB)}{20}\right)}) \tag{5-41}$$

Method 2 – Route Scan method

The two-ray model works also for the route scan method, which can be used when Method 1 can't be applied because at least one minimum and one maximum are not available. The field strength is acquired at a constant antenna height while driving along a predefined route that runs straight towards or away from the transmitter. It is important that line-of-sight condition be maintained along the route. Measurement samples are taken at high speed along the route together with the geographical coordinates of each measurement point. For each point, the measured values are compared with the theoretical ones calculated by the two-ray model. This requires the knowledge of the soil characteristics (ε_r, σ), the distance to the transmitter and the height of the reflection point with respect to the transmitting antenna. It is supposed that the reflection points are so close to

the reception antenna that the ground height offset can be neglected. The radiated transmitted power is adjusted until the average difference between the measured and the calculated field strength along the path is minimised.

Method 3 – Linear statistic or graphic method

The linear method is based, for each measurement height, on the comparison between the measured value with the theoretical ratio |R|. It can be done graphically or by applying a statistical operator. This method can be used regardless of the presence of a minimum and maximum.

To be sure that a comparison is done at the same heigh it is necessary to consider a height offset to be associated to the measuring point, which accounts for the height difference between the ground level of the wheel of the measurement vehicle and the ground level of the reflection point and for the height difference between the electrical centre of the receiving antenna and the top of the mast. Usually, the last difference is higher for vertical polarization than horizontal polarization.

For each measurement height, the theoretical ratio |R| gives an indication whether the measured value is higher or lower the direct field strength, E_d. The expected E_d at each measuring height is given by the division of E for the ratio |R|. By doing this for all measurement heights, a series of values for the expected E_d is obtained.

From that series of E_d, the mean and variance is calculated. The mean value represents the final estimation of E_d, while the variance (or standard deviation; short: STD) indicates the results accuracy. The variance is then reduced by acting recursively on the three available parameters (n_k, σ and height offset of the measuring point), until the smallest values for the variance has been found. The value for E_d is then regarded as the best estimation of the direct field strength.

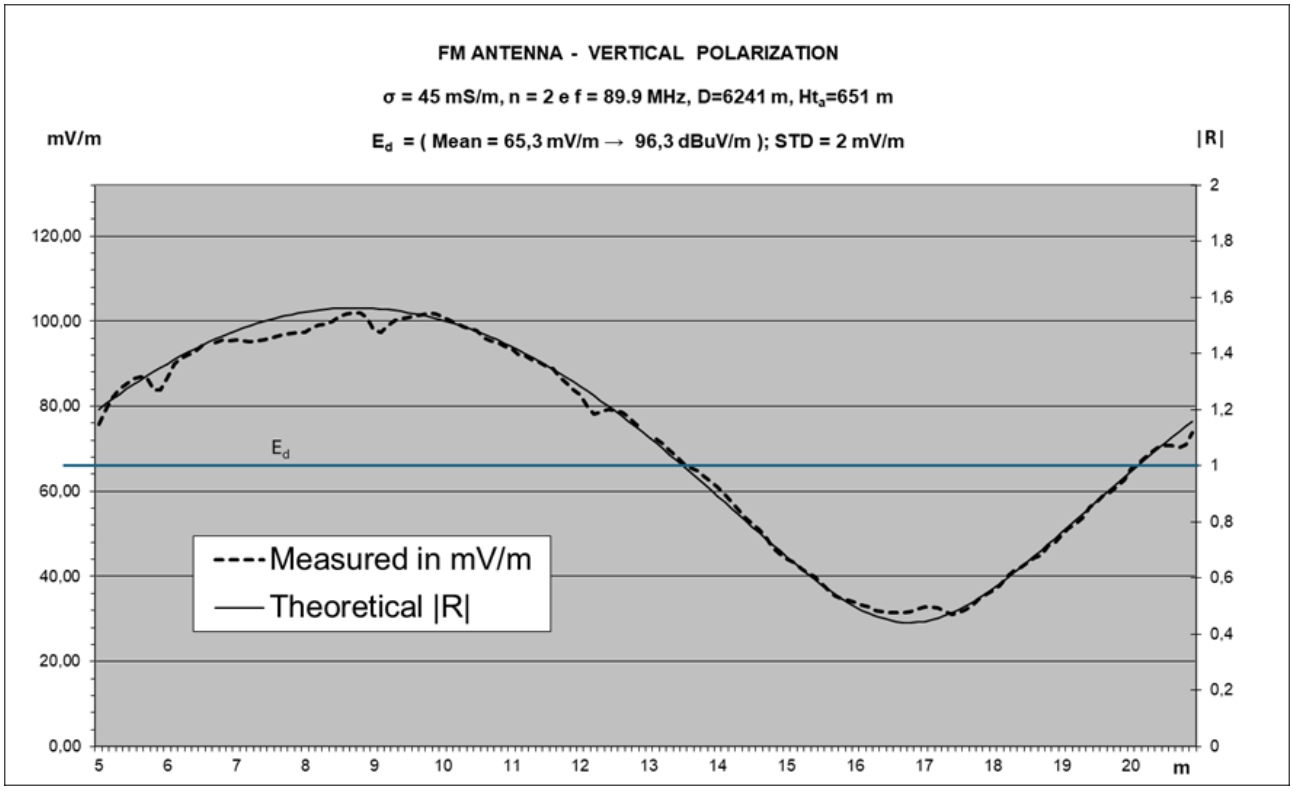
A more simple evaluation of the E_d can be done by plotting the measured field strength and the |R| curves on a double scale picture. One vertical axis is for the field strength in linear scale (e.g. mV/m), the second vertical axis is for the ratio |R|. By adjusting the three available parameters ε_r, σ and the height offset of the measurement point it is possible to match the theoretical curve with the measured one. The measured field intensity corresponding to the relative value of 1 is the sought value of the direct field strength E_d. If the graphical matching is not possible or the standard deviation of E_d is much higher than the uncertainty of the measurement chain, then the measurement point has to be discarded and a new one needs to be found.

Figure 5-27 depicts an example of a good graphical match between measured and calculated values for an VHF-FM broadcasting station.

The result for the direct field strength is: $E_d = 65{,}3$ mV/m (96.3 dBμV/m); STD = 2 mV/m.

FIGURE 5-27

Comparison of measured and estimated field strength measurement result



5.4.6.5 Uncertainty

The uncertainty elements *U* are associated with the measured values, distances, height of the transmitting and receiving antenna, conductivity and permittivity of the soil. The standard deviation (STD) derived with a recursive method takes into account the uncertainty of the distances, height and characteristics of the ground and therefore only two parameters remain to be considered: the STD itself and the standard uncertainty of the measured values (measuring instrument, calibration factor), both expressed in absolute values, e.g. in mV/m.

$$U = \sqrt{U_{E_d}^2 + U_{meas}^2} \tag{5-42}$$

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ITU-R Recommendations and Reports

NOTE – In every case the latest edition of the Recommendation and Report is encouraged to be used

Recommendation ITU-R SM.378 – *Field-strength measurements at monitoring stations*

Recommendation ITU-R P.527 – *Electrical characteristics of the surface of the Earth*

Recommendation ITU-R P.533 – *Method for the prediction of the performance of HF circuits*

Recommendation ITU-R BS.638 – *Terms and definitions used in frequency planning for sound broadcasting*

Recommendation ITU-R P.845 – *HF field-strength measurement*

Recommendation ITU-R P.1057 – *Probability distributions relevant to radiowave propagation modelling*

Recommendation ITU-R M.1172 – *Miscellaneous abbreviations and signals to be used for radio-communications in the maritime mobile service*

Recommendation ITU-R P.1546 – *Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 4 000 MHz*

Recommendation ITU-R P.2001 – *A general purpose wide-range terrestrial propagation model in the frequency range 30 MHz to 50 GHz*

Report ITU-R P.228 – *Measurement of field strength for VHF (metric) and UHF (decimetric) broadcast services, including television*

Report ITU-R BS.516 – *Field strength resulting from several electromagnetic fields*.

5.5 Bandwidth measurement

5.5.1 Bandwidth definitions

The following bandwidth definitions are relevant for monitoring stations.

5.5.1.1 Necessary bandwidth

Article **1**, No. **1.152** of the RR defines the term *necessary bandwidth* as follows:

"For a given class of emission, the width of the frequency band which is just sufficient to ensure the transmission of information at the rate and with the quality required under specified conditions."

The necessary bandwidth is a theoretical value that can be calculated using modulation-dependent formulas in Recommendation ITU-R SM.328. It cannot be measured.

5.5.1.2 Occupied bandwidth

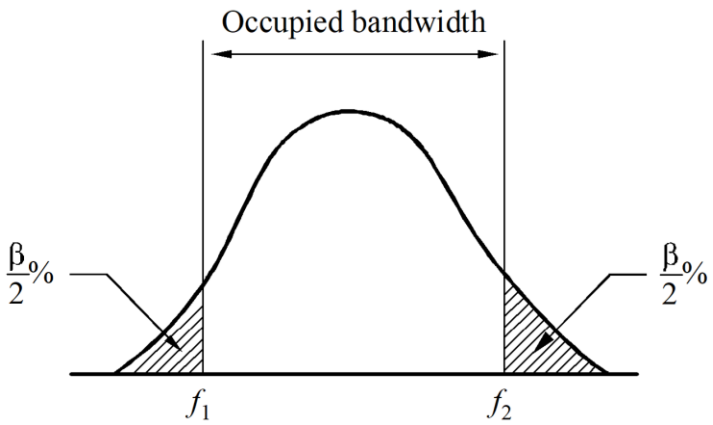
Article **1**, No. **1.153** of the RR defines the term *occupied bandwidth* as follows:

"The width of a frequency band such that, below the lower and above the upper frequency limits, the *mean powers* emitted are each equal to a specified percentage β/2 of the total *mean power* of a given *emission*. Unless otherwise specified in an ITU-R Recommendation for the appropriate *class of emission*, the value of β/2 should be taken as 0.5%."

Figure 5-28 shows the concept of occupied bandwidth.

FIGURE 5-28

Definition of occupied bandwidth as formulated in RR Article 1, No. 1.153



Ideally the occupied bandwidth of an emission should be nearly equal to the necessary bandwidth. From the simplified example in Fig. 5-28, however, it can already be seen that the concept of occupied bandwidth is a purely practical one, because it implies that part of the signal energy, namely 1%, can be neglected and that part of the spectrum is regarded as not occupied, hence "free". This fact already implies that the occupied bandwidth is wider than the necessary bandwidth.

Implementation factors such as limited linearity and amplifier noise of real transmitters also result in a higher occupied bandwidth than theoretically necessary.

5.5.1.3 X-dB bandwidth

Recommendation ITU-R SM.328 defines the term *x-dB bandwidth* as follows:

"The width of a frequency band such that beyond its lower and upper limits any discrete spectrum component or continuous spectral power density is at least *x*-dB lower than a predetermined 0 dB reference level."

Research results show that the "*x*-dB" bandwidth can be used to estimate the occupied bandwidth under well-defined conditions as to the class of emission and the modulation characteristics of the signal. There are cases, however (e.g. that of some digital modulation schemes), when the "*x*-dB" bandwidth is not a good estimate of the occupied bandwidth.

5.5.1.4 Assigned bandwidth

The assigned bandwidth is the maximum bandwidth that a station is allowed to occupy. In the Radio regulations, the term "assigned frequency band" is used and defined as follows:

"The frequency band within which the *emission* of a *station* is authorized; the width of the band equals the *necessary bandwidth* plus twice the absolute value of the *frequency tolerance*. Where *space stations* are concerned, the assigned frequency band includes twice the maximum Doppler shift that may occur in relation to any point of the Earth's surface."

The assigned bandwidth is a value that is usually stated in the license. Like the necessary bandwidth, it is a theoretical or, in this case, an administrative value that cannot be measured.

5.5.2 Bandwidth determination at monitoring stations

Monitoring stations may need to measure the bandwidth of an emission for the following reasons:

To characterize an (unknown) emission:

Among other properties, the occupied bandwidth of an emission, when compared to the necessary bandwidth, can provide valuable information on the nature of an (eventually unknown) signal.

To validate compliance with license conditions:

If the occupied bandwidth of an emission exceeds the assigned bandwidth, it may be regarded as a violation of the license conditions, or it may cause interference to neighbouring channels.

In any case, monitoring stations usually have the task to determine the occupied bandwidth. Only in some rare cases, such as for Radar emissions, the x-dB bandwidth may be defined in the license.

With modern spectrum analysers, the occupied bandwidth can be measured directly using the ß%-method in most situations, in which case it should be the preferred method. Only in the following cases, the x-dB method may be more suitable:

- The measurement equipment is not capable of performing the ß%-method
- In-band interfering signals are higher in level than -x dB
- The x-dB value is stated in the license.

Both measurement methods are described in detail in Recommendation ITU-R SM.443.

Digital signals usually have a noise-like time behaviour, resulting in a constant bandwidth. Analogue modulated signals have a time-varying bandwidth that depends on the modulation signal. In those cases, monitoring stations are only interested in the maximum occupied bandwidth.

5.5.2.1 Suitable measurement equipment

Realtime spectrum analysers and broadband receivers can capture the whole frequency channel of interest at once and calculate the occupied bandwidth by integration of the spectrum that results from an FFT. Since all parts of the spectrum have been recorded at the same time, this type of equipment yields the most accurate results. Furthermore, it can also be used to measure the momentary bandwidth of analogue or pulsed signals.

Sweeping analysers can also be used. However, they need a certain time to record the spectrum which means that the left end of the spectrum trace was recorded earlier than the right end. While this is not problematic in the case of digital signals, the momentary bandwidth cannot be measured as the MaxHold function has to be used.

Almost every modern measurement receiver and analyser has a function to measure the bandwidth of a signal. However, certain measurement conditions have to be assured that require some measurement parameters to be set manually, as described in the following sections.

5.5.2.2 Prerequisites for measuring bandwidths

Depending on the measurement method, and the RF properties of the signal, a certain minimum signal-to-noise ratio (S/N) is required to obtain a valid result. Furthermore, it has to be assured that in-band interfering signals and signals on neighbouring frequencies do not influence the result. This is the reason why fully automatic or 'blind' bandwidth measurements without the possibility to see the actual spectrum are not recommended.

First the span should be selected wide enough to consider the full signal (a bit wider than the expected OBW); then the resolution bandwidth has to be set.

The type of instrument governs the choice of the optimum resolution bandwidth:

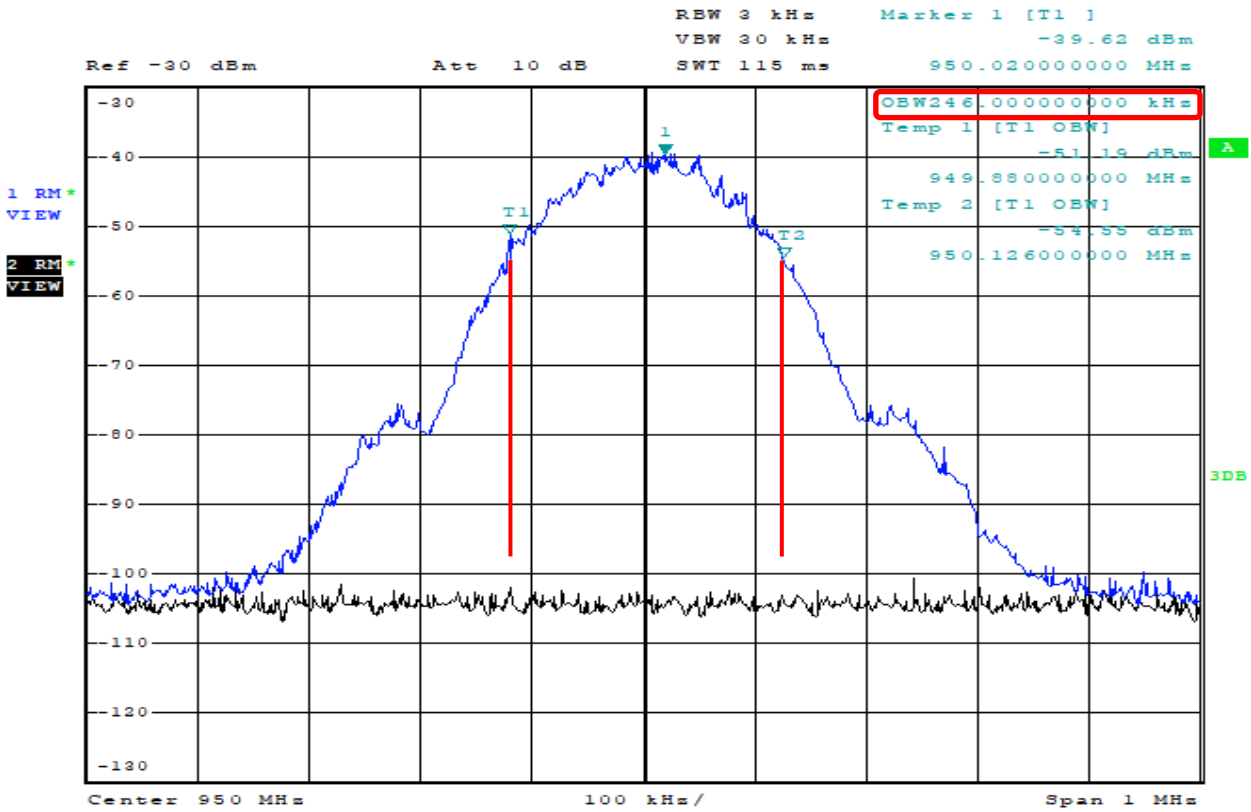
For swept spectrum analysers, the RBW is the span divided by the number of horizontal pixels. For example, if the span is 1 MHz and the screen shows 500 horizontal pixels, then the optimum RBW is 2 kHz. A larger RBW would produce too wide bandwidth results.

If a real-time analyser or broadband measurement receiver is used, the optimum RBW is equal to the number of FFT points.

Figure 5-29 shows an example of a valid bandwidth measurement of a GSM signal with sufficient *S*/*N* and in the absence of interferers. The result of the occupied bandwidth measurement is given in the red box (246 kHz)

FIGURE 5-29

Occupied bandwidth measurement (99%) under ideal conditions with a swept spectrum analyser on a GSM signal



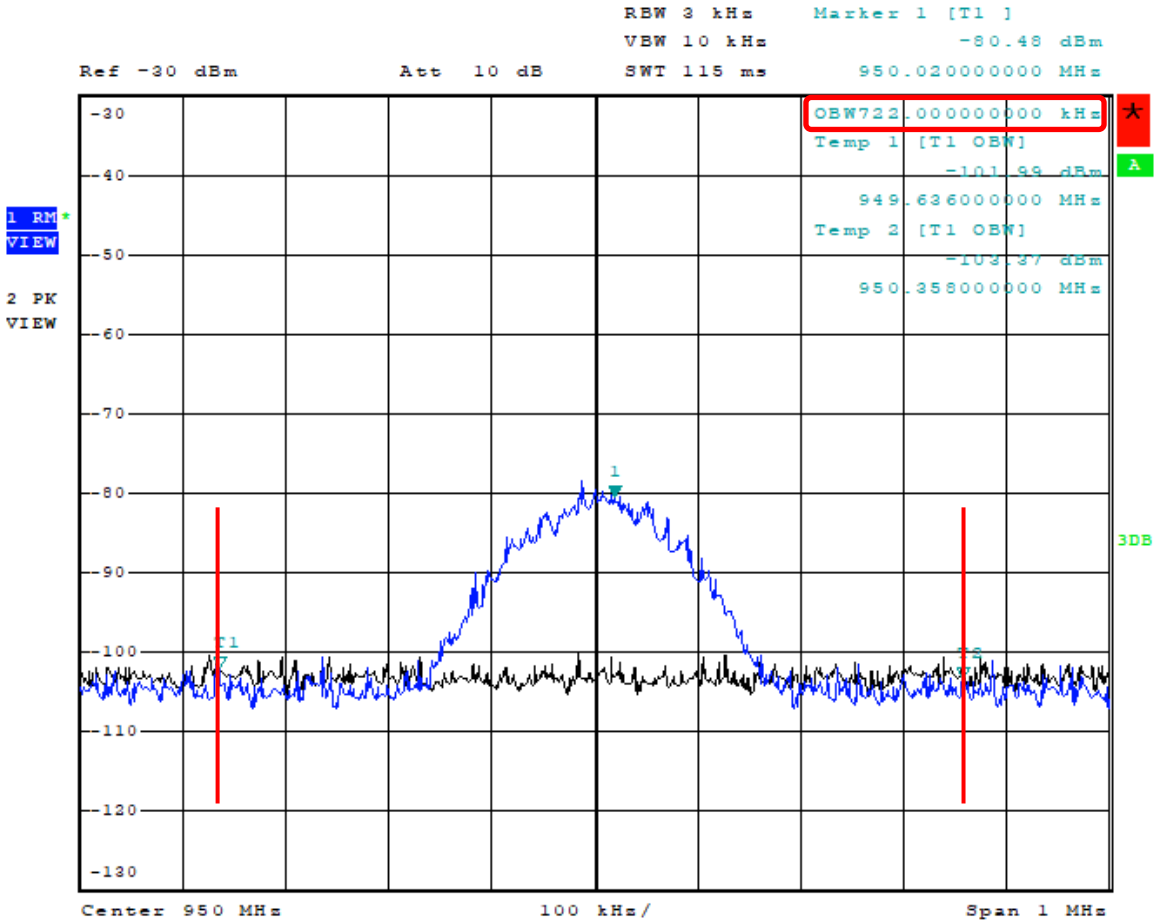
5.5.2.3 Practical considerations and limitations of the ß%-method

As mentioned above, the ß% method relies on graphical integration of spectral densities around the wanted frequency. It is therefore important to ensure that the span (or integration bandwidth) is wide enough to cover all receivable signal components, but narrow enough not to include neighbouring signals. In the absence of interference, this can be ensured by recording a second trace with the same settings, but disconnected signal, then showing the analyser noise (see the black trace in Fig. 5-29).

All spectral components within the span – including receiver noise - will be treated as signals coming from the transmitter and be included in the integration process. Especially in low *S*/*N* conditions it is therefore important not to set the span too wide, as shown in the example in Fig. 5-30.

FIGURE 5-30

Example of a ß% bandwidth measurement with low *S/N* and too wide span setting



The same caution of the span settings applies when strong signals on neighbouring channels are present. Figure 5-31 shows an example of a digital signal in the HF range with an adjacent AM broadcast signal. The *S/N* is about 25 dB. The measurement or integration bandwidth is set to 10 kHz. The result of the 99% bandwidth is 2.98 kHz which could be plausible. However, from the spectrum display it can be seen that the Broadcast signal is included in the measurement, leading to an incorrect result. Figure 5-32 shows the same signal with correct span settings.

FIGURE 5-31

Example of a bandwidth measurement with adjacent interferer and too wide span setting

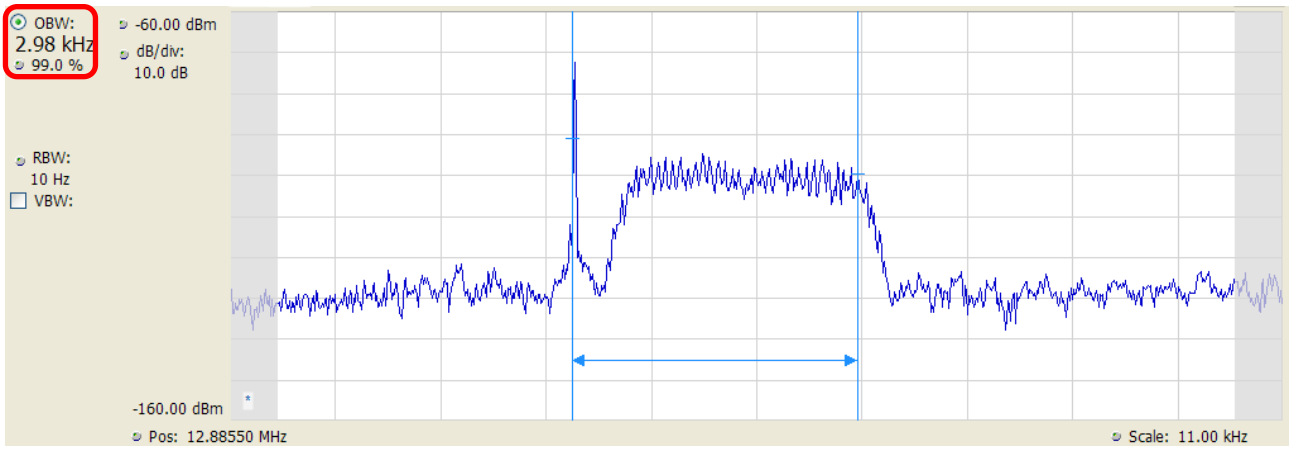
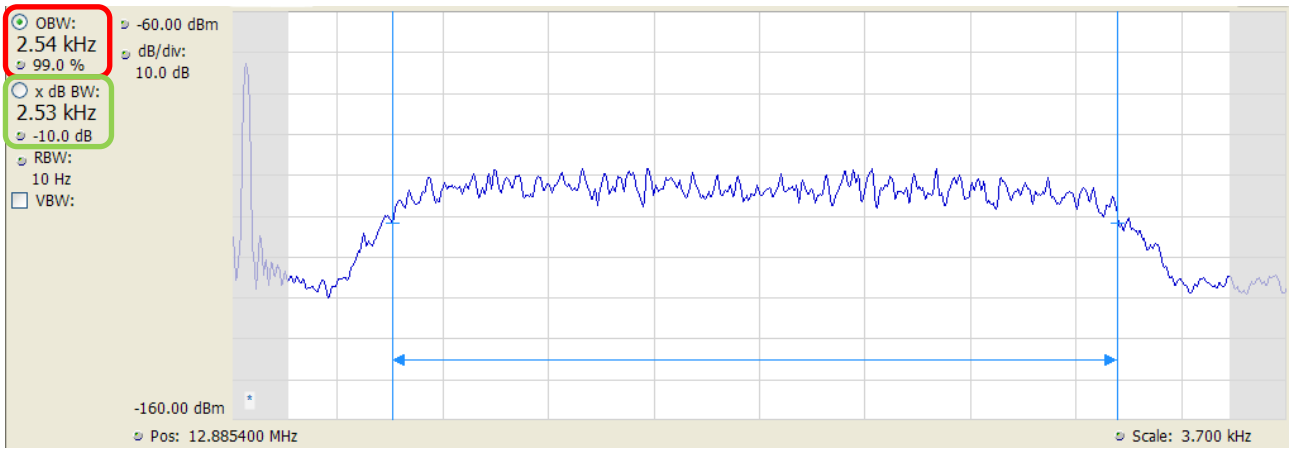


FIGURE 5-32

Example of a bandwidth measurement with adjacent interferer and correct span setting



In any case, the SNR required to perform bandwidth measurement with the 99% power method need not be unreasonably high; on many signals, accurate results can be obtained with 15 to 20 dB of SNR (defined here as the difference of peak signal and of noise floor), which is a reasonable value in many cases, and lower than 26 dB.

5.5.2.4 Practical considerations and limitations of the x-dB method

The x-dB bandwidth can be directly measured with a spectrum analyser, either by manually setting markers that are a specified number of dB below the maximum level ('0 dB reference'), or by using automatic functions built into most modern analysers. The most critical parameters are the 0 dB reference level and the value for x that results in the best approximation of the occupied bandwidth, if that is the desired bandwidth. Both parameters depend on the nature and modulation of the signal to be measured.

For analogue signals, the 0 dB reference level is usually the total signal power which can be determined by setting an RBW or receiver bandwidth that is at least as wide as the whole signal. Care should be taken not to include parts of neighbouring emissions when selecting the receiver bandwidth.

For digital signals, the reference is usually the maximum power spectral density (psd) determined with the same narrow RBW or measurement bandwidth that is used for the actual bandwidth measurement. In case of analogue signals, first the reference level is measured with a wide RBW, while for the determination of the x-dB bandwidth and of the maximum power density of digital signals, the optimum RBW is equal to the horizontal screen resolution of the spectrum display.

Table 5-8 contains empirically determined values for x for some classes of emissions that best approximate the occupied bandwidth.

TABLE 5-8

Empirically-derived value of "*x*-dB" level at which "*x*-dB" and occupied bandwidths are close to each other

Class of emission (See RR Appendix 1)	Values of "*x*-dB" to be used when measuring "*x*-dB" bandwidth for estimation of occupied bandwidth	Remarks
A1A A1B	–30	For $\alpha^{(1)} \geq 3\%$ (all pulse shapes)
A2A A2B	–32	For a modulation depth between 80 and 90%
A3E	–35	
B8E	–26	

TABLE 5-8 *(end)*

Class of emission (See RR Appendix 1)	**Values of "*x*-dB" to be used when measuring "*x*-dB" bandwidth for estimation of occupied bandwidth**	**Remarks**
F1B	−25	For all signal shapes and a modulation index $2 \leq m \leq 24$
F3C	−25	For all types of transmitted pictures and modulation indexes $0.4 \leq m \leq 3$
F3E G3E	−26	
F7B	−28	
H2B H3E J2B J3E R3E	−26	
C7W (8-VSB)	−12(2)	Average of more than 300 sweeps
GMSK, GFSK	−15	(see example in Fig. 5-29)
QPSK, QAM	−10	Cos- and RRC-filtered (see example in Fig. 5-32)
G7W (OFDM)	−8(2)(3)	Average of more than 100 sweeps

(1) The relative build-up time, α, of a telegraph signal is defined in § 1.10 of Recommendation ITU-R SM.328.

(2) According to Recommendation ITU-R SM.328, the unit of these values is dBsd because the reference level was chosen to the maximum value of power spectral density (psd) within the necessary bandwidth.

(3) This value is derived from experiments with T-DMB using a T-DAB network taken from Report ITU-R BT.2049.

Report ITU-R SM.2048 introduces the concept of measuring the −30 dB bandwidth and applying modulation-specific conversion factors to determine the necessary bandwidth. Although this does not provide an exact determination of the occupied bandwidth, it may serve as an estimate allowing the identification of systems and detecting faulty transmitters producing a far wider spectrum than necessary.

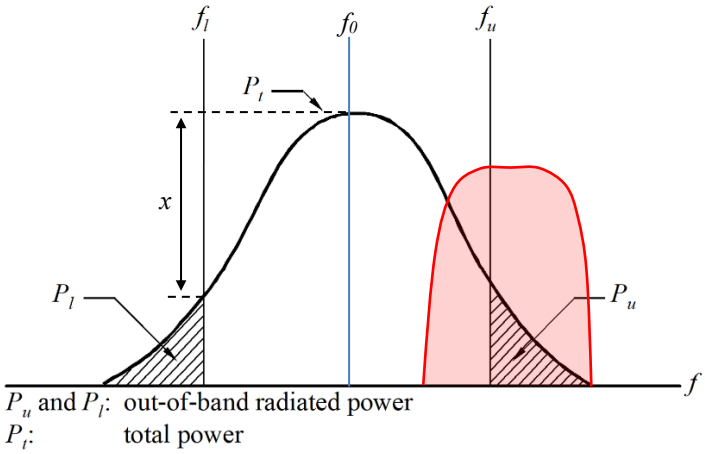
5.5.2.5 Comparison of the measurement methods

From Table 5-8 it can be seen that especially for analogue signals, often certain modulation parameters have to be known in order to determine the correct value for x. This is not necessary when using the ß%-method. Furthermore, the x-dB method can only approximate the occupied bandwidth, whereas the ß%-method can measure it directly.

The x-dB method has its main advantages when the wanted signal is partly masked by interference. Figure 5-33 shows an example of such a situation.

FIGURE 5-33

X-dB bandwidth measurement with inband interferer



Even if the level of the interfering signal is less attenuated than the x-dB value, a bandwidth measurement is still possible using only one half of the symmetric spectrum. An example is shown in the Figure from f_l to f_0.

Another specific case where the x-dB method is more appropriate than the ß%-method are OFDM signals. Unlike other modulations, their rectangular spectrum has a uniform power spectral density across the whole bandwidth, up to the very edges. The occupied bandwidth of OFDM signals is therefore more reasonably defined as the frequency difference between the outer subcarriers, which is easily measured using the x-dB method. A ß%-measurement would disregard 1% of the outer subcarriers, although they are transmitted with the same power as any other subcarrier.

References

NOTE – In every case the latest edition of the Recommendation or Report is encouraged to be used.

ITU-R Recommendations and Reports

Recommendation ITU-R SM.328 – *Spectra and bandwidth of emissions*

Recommendation ITU-R SM.329 – *Unwanted emissions in the spurious domain*

Recommendation ITU-R SM.443 – *Bandwidth measurement at monitoring stations*

Report ITU-R SM.2048 – *Use of the x dB bandwidth criterion for determination of spectral properties of a transmitter in the out-of-band domain*

Report ITU-R BT.2049 – *Broadcasting of multimedia and data applications for mobile reception*.

5.6 Modulation measurement

5.6.1 Introduction

The basic fundamentals of the various modulations are covered in § 7.6. Section 5.6 focuses on the measurement of different modulation parameters, the identification of the modulation and analysis methods only. Please refer to that section regarding specific terms and symbols.

5.6.2 Suitable measurement instruments

The instruments suitable for modulation measurements can be divided into three groups:

– General purpose instrumentation: Spectrum analyser, analogue monitoring receiver and oscilloscope. The use is limited to analogue modulation measurements or for specific parameters of digital modulation.

– Dedicated devices: Modulation meter and modulation analyser.

– Digital monitoring receiver and vector signal analyser (VSA) with digital processing capabilities. This type of equipment may allow measurement of all modulation parameters.

5.6.3 Analogue modulation

5.6.3.1 Amplitude modulation

The key parameter to measure in analogue amplitude modulation (AM) is the modulation depth m given by:

$$m(\%) = \frac{E_{max} - E_{min}}{E_{max} + E_{min}} \cdot 100\% \tag{5-43}$$

For normal operative states of the transmitter, m is in the range between 0 and 100% and can directly be read from measurement receivers.

An anormal state is reached for $m > 100\%$. The transmitter is said to be 'overmodulated'. This occurs if $E_{min} < 0$. However, it is not indicated by a measurement receiver. Instead, another definition of the modulation depth is applied that uses the carriers average amplitude:

$$\pm m(\%) = \frac{E_{max} - E_{min}}{2 \cdot E_c} \cdot 100\% \tag{5-44}$$

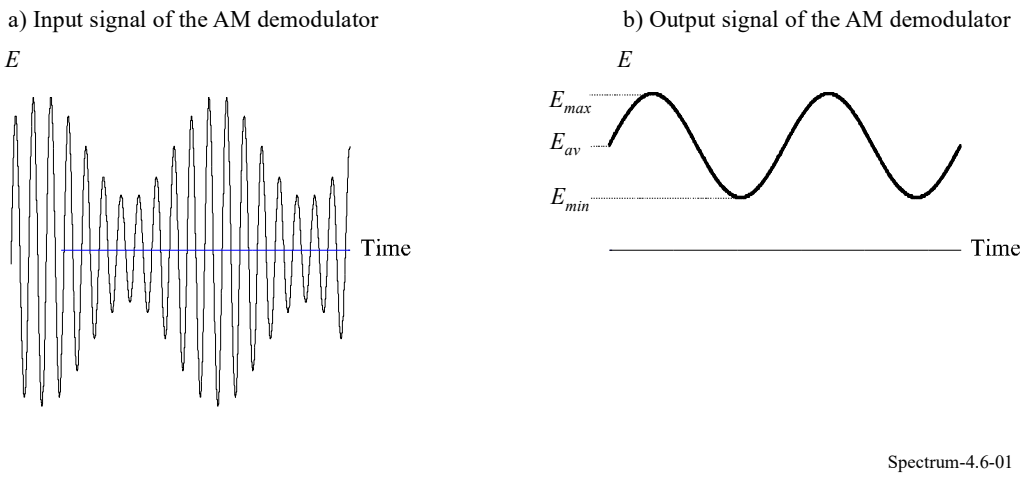
The measurands in equation (5-44) can be taken with measurement receivers or spectrum analysers. If $m_+ = m_- = m_\pm$, the modulation can be considered symmetrical (i.e. the value of the carrier amplitude $E_c$is not changed by the modulating signal), the modulation percentage is < 100% and no overmodulation occurs.

Some modulation analysers allow a more thorough investigation of radio frequency and audio frequency related parameters of that signal. These include the carrier frequency, distortion of the audio signal or the demodulated signal-to-noise ratio.

The output of the AM demodulator is, for example, the positive envelope voltage of the carrier wave, as shown in Fig. 5-34: Fig. 5-34 a) shows the input and Fig. 5-34 b) shows the output signal of the demodulator.

FIGURE 5-34

Input and output signals of the AM demodulator



The indication circuit now calculates the modulation depth. Correspondingly, the instrument Comparison of these values shows whether modulation is non-symmetrical or overmodulated.

Sometimes only the instantaneous values of the modulation depth corresponding to modulation peaks are required to check that there is no overmodulation, even for longer periods of time. A spectrum analyser with zero span (time domain) or a vector signal analyser may also be used; even an oscilloscope connected to the intermediate frequency output of a receiver may be sufficient.

Further information on AM is given in § 7.6.2.1.

5.6.3.2 Frequency and phase modulation (FM/PM)

As explained in § 7.6, frequency and phase modulation (FM/PM) are basically the same and result in the same RF signal. For frequency/phase modulated signals, the key parameter to measure is the instantaneous frequency deviation Δf from the carriers' centre frequency which can directly be read from standard measurement receivers.

The modulation index m is given by the ratio the deviation Δf and the frequency of the modulating (low frequency) message signal:

$$m = \frac{\Delta f}{f_m} \tag{5-45}$$

All properties of frequency and phase deviations can be measured using modulation meters. Another possibility to measure the deviation of FM broadcasting stations is the application of an IFM-based modulation domain analyser (see § 5.2.2.4), a monitoring receiver or vector signal analyser. The sampling rate must be chosen according to the modulation (e.g. at a minimum of 40 kSamples/s if the maximum modulating frequency is 15 kHz). The measuring repetition time (time window) should correspond to the lowest frequency at which we wish to determine the deviation. The longer the measuring time, the lower is the modulation frequency that can be seen after processing the samples.

Phase and frequency deviation measurements of wanted signals are performed as peak value measurements, because by definition, phase and frequency deviations of communication signals are peak deviations. However, if noise or signal-to-noise or SINAD (signal in noise and distortion) measurements have to be performed, r.m.s. values or quasi-peak weighted values of the respective deviations have to be taken into consideration. Therefore, PM and FM meters are usually equipped with detectors to give r.m.s., SINAD and quasi-peak results as well. Sometimes, certain audio weighting filters have to be applied. More information regarding the specific procedures and weighting functions are described in Recommendation ITU-R BS.468.

Measurement and evaluation of maximum deviation and modulation power of FM broadcast emissions over the air during normal programme operation is described in detail in Recommendation ITU-R SM.1268.

Further information on FM/PM is given in §§ 7.6.2.2 and 7.6.2.3.

5.6.3.3 Simultaneous measurement of AM and PM/FM

Multipath propagation is a general problem for FM signals. The result of multipath propagation in FM systems is unacceptable distortion of the modulated signal. Due to multipath propagation, PM or FM is converted into a certain percentage of AM at the receiving location. Therefore, multipath situations can be seen by measuring the AM of a frequency-modulated carrier. For this purpose, the modulation meter has to measure the modulation indices for AM and PM/FM simultaneously.

For this purpose, instruments are available which offer parallel measurements of frequency deviation and amplitude modulation depth with immediate calculation of the conversion factor, expressed in % modulation depth over kHz FM deviation.

Recommendation ITU-R SM.1268 defines maximum values for the amount of AM as well as a measurement procedure for multipath determination and how to rate the validity of a deviation measurement.

5.6.3.4 Special analogue modulations

5.6.3.4.1 TV broadcast modulations

One important property of the modulation of analogue TV broadcast (Vestigial sideband, VSB) transmissions in the VHF/UHF bands is the level of the subcarriers (e. g. for sound and colour burst) relative to the vision carrier. This can be measured with a spectrum analyser using a resolution bandwidth of at least 100 kHz. The nominal values are system dependent and can be taken out of the appropriate standard documentation.

According to the respective standard, parts of the TV signal are kept constant in amplitude, independent of the picture content. For this reason, conventional modulation depth measurement of the video modulation makes no sense.

The presentation of the IF signal or demodulated video signal on an oscilloscope is useful and gives a good impression of the modulation. A minimum bandwidth of 5.5 MHz of the IF output and – if used – the video demodulator of the receiver is a prerequisite for the correct presentation.

Special analogue TV analysers are available that allow the detailed analysis of the picture modulation including contents of the test lines inserted between subsequent frames.

Deviation measurements of the sound channels can be performed in the conventional way, provided that the selectivity of the modulation meter is sufficient.

5.6.3.4.2 Single sideband (SSB) modulation with suppressed carrier

With this modulation type, the carrier is suppressed and the modulation depth is not defined. Consequently, the modulation depth cannot be measured.

5.6.3.4.3 Independent sideband (ISB) modulation

The statements above regarding single sideband (SSB) with suppressed carrier also apply to independent sideband modulation (ISB) with suppressed carrier (B8E).

No measurement of the modulation characteristics in the conventional way is possible.

5.6.3.4.4 Dynamic amplitude modulation

As explained in § 7.6, this modulation reduces the carrier level whenever the modulation depth is low to save transmit energy. The carrier power is a function of the modulation level. In this case, without knowledge of details of the characteristic of the transmitted signal, the indication of a conventional modulation meter cannot be correct. To find out whether Dynamic amplitude modulation (DAM) is used or not, the average carrier level has to be measured with a slow time-constant.

5.6.4 Single carrier digital modulation

Depending on certain system parameters, single carriers being amplitude, frequency and/or phase modulated such as ASK, FSK, PSK, MSK and QAM have similar if not equal spectra and cannot easily be distinguished using a swept spectrum analyser. Measurements of the modulation depth and frequency deviation using standard modulation meters or measurement receivers are often not possible. Instead, the following modulation properties may be of interest:

– identification of modulation and number of constellation states;

– symbol rate;

– baseband filtering;

– modulation errors.

5.6.4.1 Symbol rate

In order to decode a digital signal, the receiver must be time-synchronized to the transmitter which means that the symbol rates must match exactly. Unless the equipment used has digital signal identification capabilities, monitoring receivers and vector signal analysers only work when the correct symbol rate has been entered by the operator. Standard measurement equipment cannot measure the symbol rate and if it is unknown, further analysis and decoding is not possible.

Due to the smooth change of amplitude and/or phase of baseband filtered signals, it is generally not possible to measure the symbol rate with an oscilloscope connected to the IF of a monitoring receiver.

As a rule of thumb, however, it can be taken that the symbol rate is roughly equal to the occupied bandwidth of the signal. Table 5-9 shows some examples for common digital single carrier systems.

TABLE 5-9

Symbol rates and bandwidths of example single carrier systems

System	Bandwidth	Symbol rate
TETRAPOL	7.2 kHz	8 kSymb/s
TETRA	21 kHz	18 kSymb/s
DECT	1.1 MHz	1.152 MSymb/s
GSM	250 kHz	270.833 kSymb/s
UMTS (European)	4.2 MHz	3.84 MSymb/s
Bluetooth	950 kHz	1 MSymb/s
WLAN DSSS (802.11b and above)	13 MHz	11 MSymb/s

Digital modulation analysers and suitably equipped monitoring receivers are able to measure the symbol rate by applying the methods as explained in the next section.

5.6.4.2 Identification of modulation and number of constellation states

As said earlier, it is not possible to uniquely identify each single carrier modulation with standard measurement receivers or swept spectrum analysers. However, certain hints can be obtained by measuring the difference between the peak and r.m.s. level (for pulsed signals: the difference between peak and average burst level). For details see § 5.3. This difference is called the crest factor. If it is zero (both levels are equal), the modulation can only be FSK, PSK or MSK, because all other single carrier modulations have an inherent amplitude modulation.

For FSK and MSK modulations, the frequency shift can be measured with an oscilloscope connected to the IF of a standard measurement receiver.

For ASK modulation, the modulation depth can be measured with a spectrum analyser in zero span mode or an oscilloscope connected to the IF of a standard measurement receiver.

To further identify the modulation used, equipment performing the functions of a vector signal analyser or FFT analyser/receiver is needed that is capable to retain amplitude, frequency and phase of the modulating signal. After entering the symbol rate, these analysers/receivers allow displaying the constellation diagram like in Fig. 5-34. For details on the constellation diagram, see § 7.6.

Further information on the modulation properties can be gained if the analyser also displays the RF vector between the constellation points (i.e. continuously at any time). The resulting display is commonly called vector diagram. Figure 5-36 shows the vector diagram of the 8-PSK signal from Fig. 5-35.

FIGURE 5-35

Constellation diagram of an 8-PSK signal

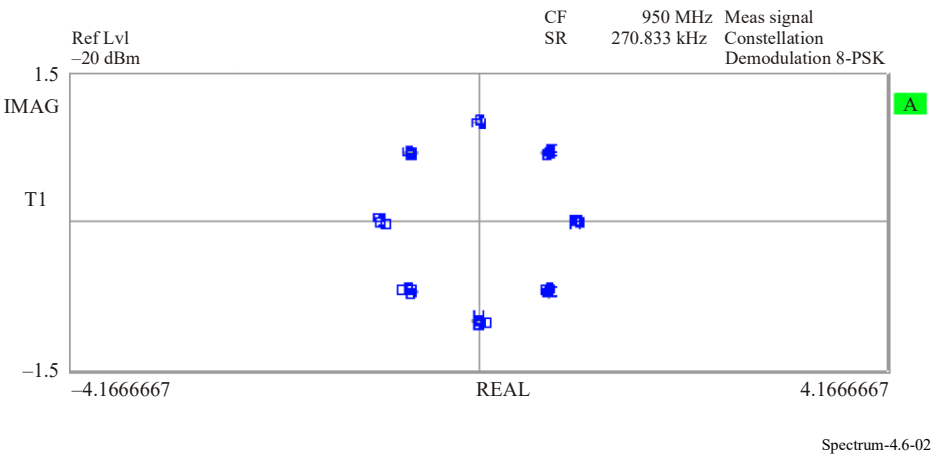
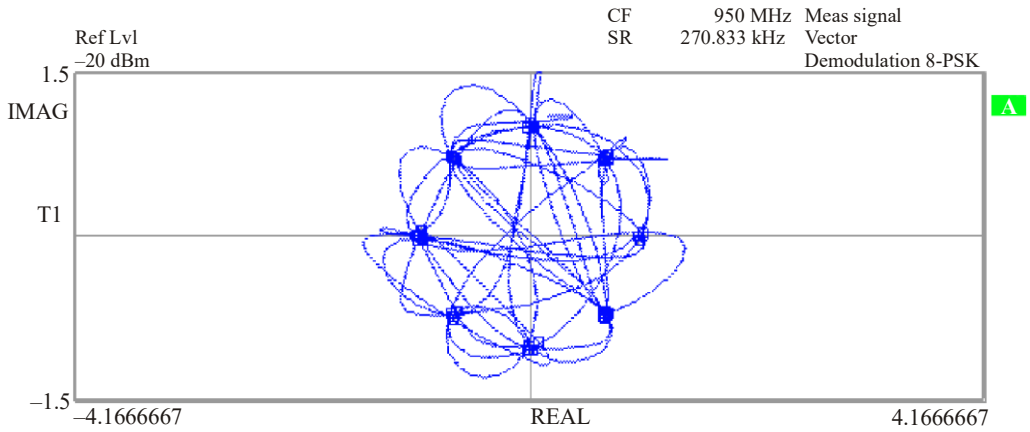


FIGURE 5-36

Vector diagram of an 8-PSK signal



Spectrum-4.6-03

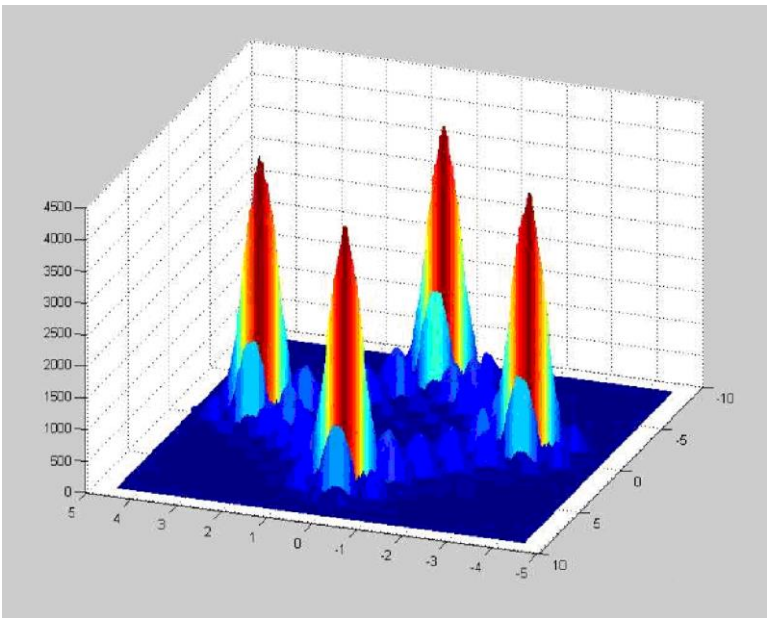
Special digital modulation analysers are available that allow under certain conditions the identification of the modulation and the measurement of the symbol rate of a complete unknown signal. These analysers are often software solutions running on a standard PC and fed with a pre-recorded sequence of the signal under investigation. Measurement techniques are based on signal transform functions such as:

Spectrum correlation and moments method

A cyclic autocorrelation of the spectra derived from several subsequent FFT processes is performed. The result may be plotted as a three-dimensional diagram showing distinct peaks at the constellation points and the time it takes for the transition between them. An example is given in Fig. 5-37 for the case of a BPSK signal. More information on the concept of cyclostationarity and moments can be found in Report ITU-R SM.2355.

FIGURE 5-37

Spectrum correlation result of a BPSK signal



Spectrum-4.6-04

Spectrum of the signal raised to the power of N

This method is based on the Fourier Transform of the signal previously raised to the power of 2 or 4. Depending on the modulation, the result shows distinct peaks which represent the number of constellation states.

Histogram method

A histogram of instantaneous frequencies or amplitudes or phases is calculated.

Depending on the modulation type, the values of calculated peaks characterize the modulation parameters.

Spectrum of zero-crossing

This method evaluates the momentary frequency of the complex baseband of the input signal. The centre frequency of this baseband is zero. The zero-crossing function now creates a peak in the time domain whenever the frequency of the (modulated) baseband signal crosses zero. Then the times between consecutive peaks t_n of the zero-crossing function are determined and a new "spectrum" is calculated using the relation $f = 1/t_n$. Figure 5-38 illustrates the process. The output of the procedure can be seen in Fig. 5-39.

FIGURE 5-38

Principle of the zero crossing method

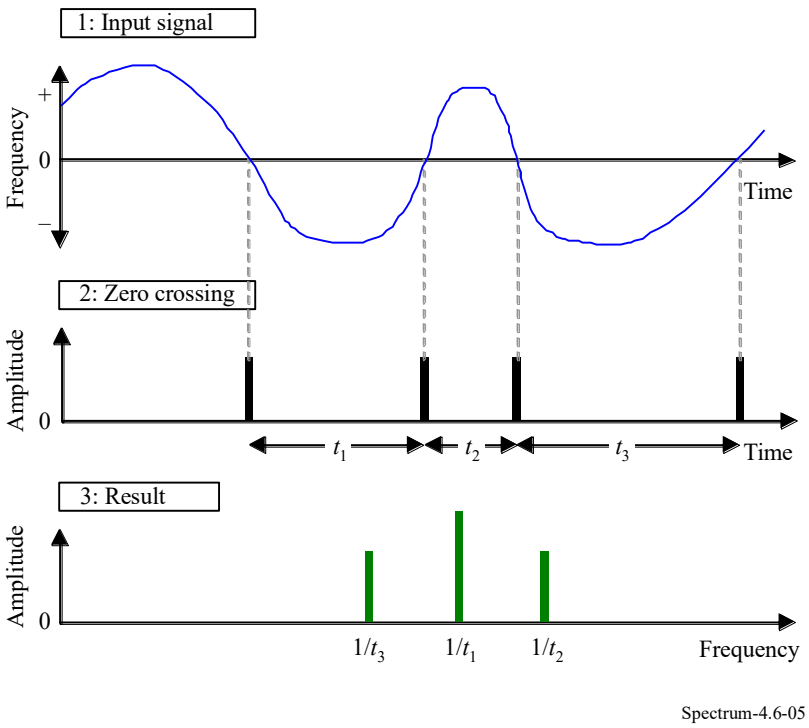
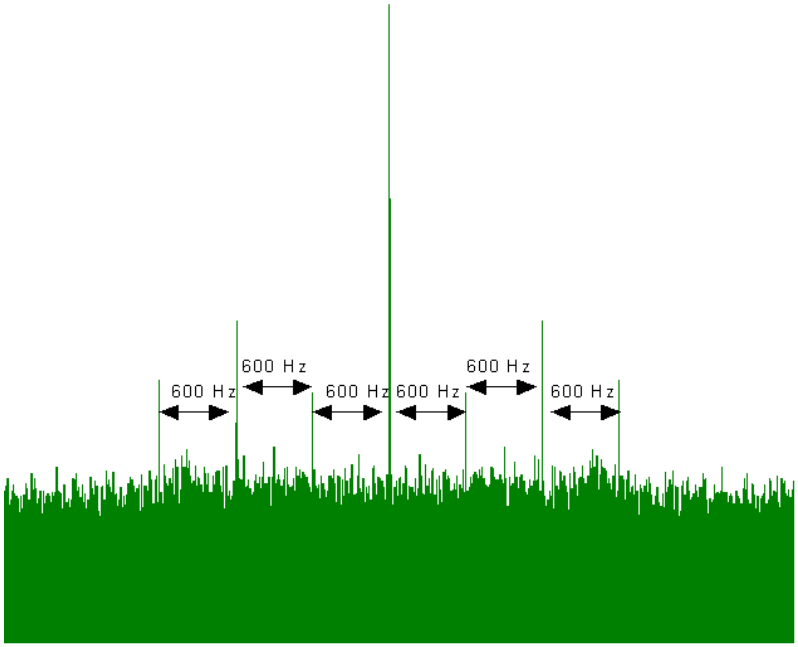


FIGURE 5-39

Zero crossing for a QPSK signal with 600 symb/s



These methods often provide more information than just the number of modulation states. Table 5-10 summarizes the capabilities of each of the methods mentioned above.

TABLE 5-10

Possible measurement methods for digital modulation parameters

Modulation	**Measurement of...**	**Spectrum correlation and moments method**	**Spectrum of the signal raised to the power of *N***	**Histogram method**	**Spectrum of zero-crossing**
ASK	Carrier frequency	√			
	Symbol rate		√ ($N = 2$)		
	Number of states			√	
FSK	Carrier frequency			√	
	Symbol rate	√			√
	Number of states		√ ($N = 1$)*	√	
PSK	Carrier frequency	√	√ ($N = 2$)		
	Symbol rate		√ ($N = 2$or 4)	√	√
	Number of states			√	
MSK	Carrier frequency		√ ($N = 2$)		
	Symbol rate		√ ($N = 2$)		√
	Number of states			√	
QAM	Carrier frequency	√			
	Symbol rate		√ ($N = 4$)		√
	Number of states	(Not possible with these methods)			

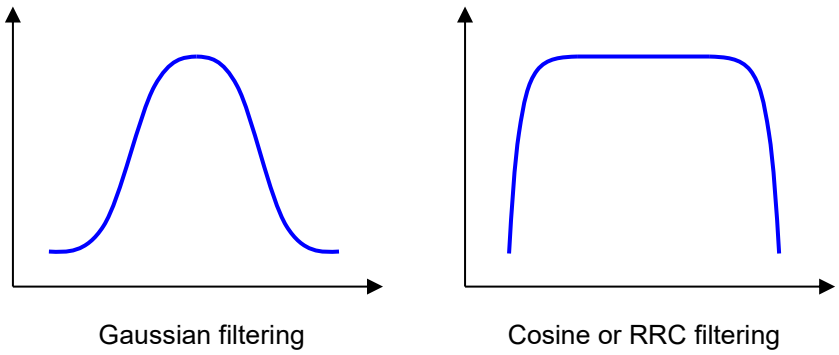
* Depending on modulation index.

5.6.4.3 Baseband filtering

As explained in § 7.6, only Gaussian, Cosine or root raised cosine (RRC) filtering is used to limit the bandwidth of digital single carrier signals and control inter-symbol-interference. These baseband filter functions lead to a characteristic shape of the RF spectrum, as illustrated in Fig. 5-40.

FIGURE 5-40

Spectra of filtered digital single carrier signals



A vector signal analyser is usually capable of displaying the I and Q components of the modulating signal in the time domain. Figures 5-41 and 5-42 show this with the example of a QPSK modulated signal for the length of 10 symbols. In Fig. 5-41, no baseband filtering was applied. Figure 5-42 shows the same signal with cosine baseband filtering. Baseband filtering 'smooths' the sharp edges in the modulating baseband pulse, while still ensuring that the RF vector reaches the nominal constellation points exactly at the time of decoding.

The smoother changes of the I and Q components result in 'overshooting' the constellation points which raises the peak amplitude of the RF signal. However, the bandwidth is significantly reduced.

FIGURE 5-41

Vector diagram and I/Q time domain of an unfiltered QPSK signal

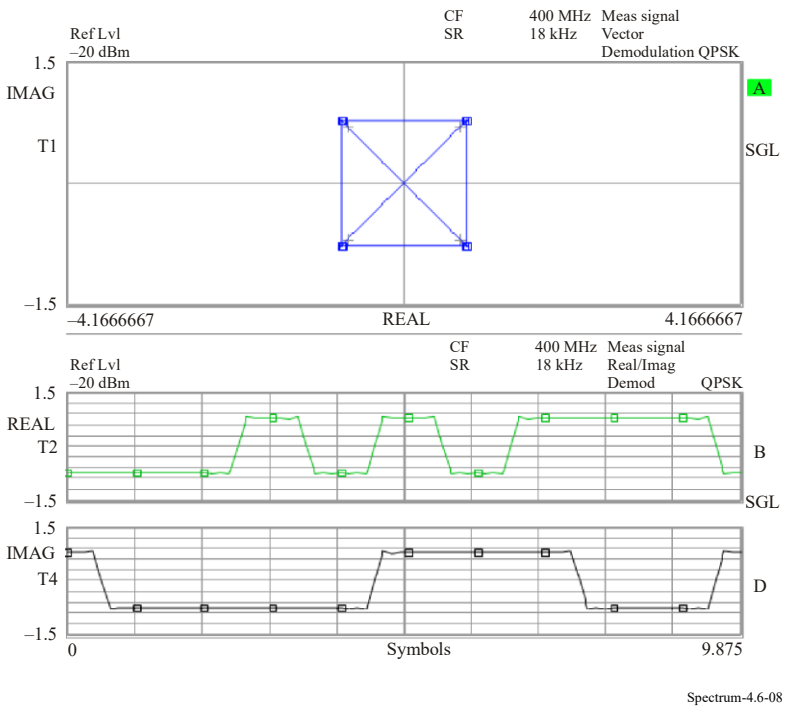
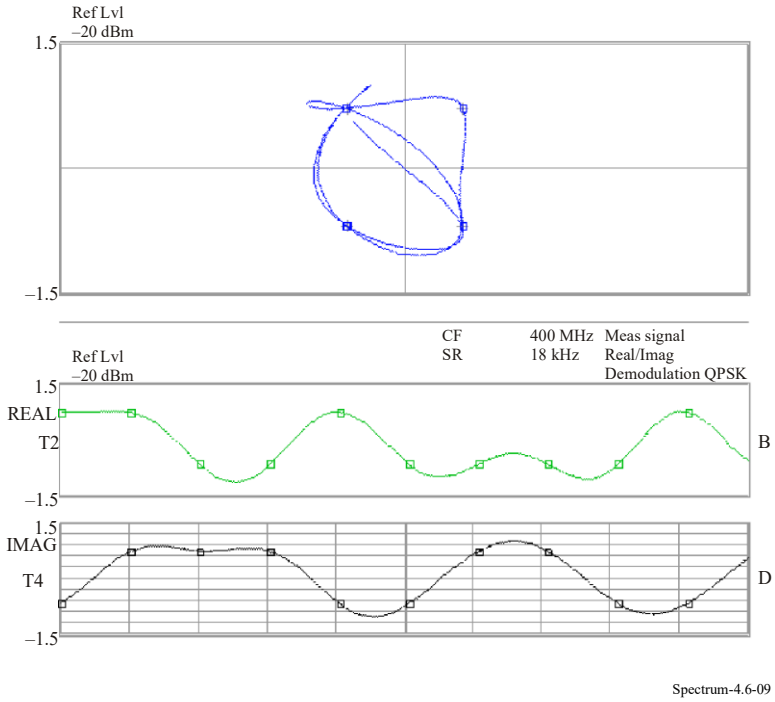


FIGURE 5-42

Vector diagram and I/Q time domain of a QPSK signal with Cosine filtering



5.6.4.4 Modulation error

Vector signal analysers and modern digital monitoring receivers are usually also capable to measure at least the following errors:

– quadrature offset;

– gain imbalance;

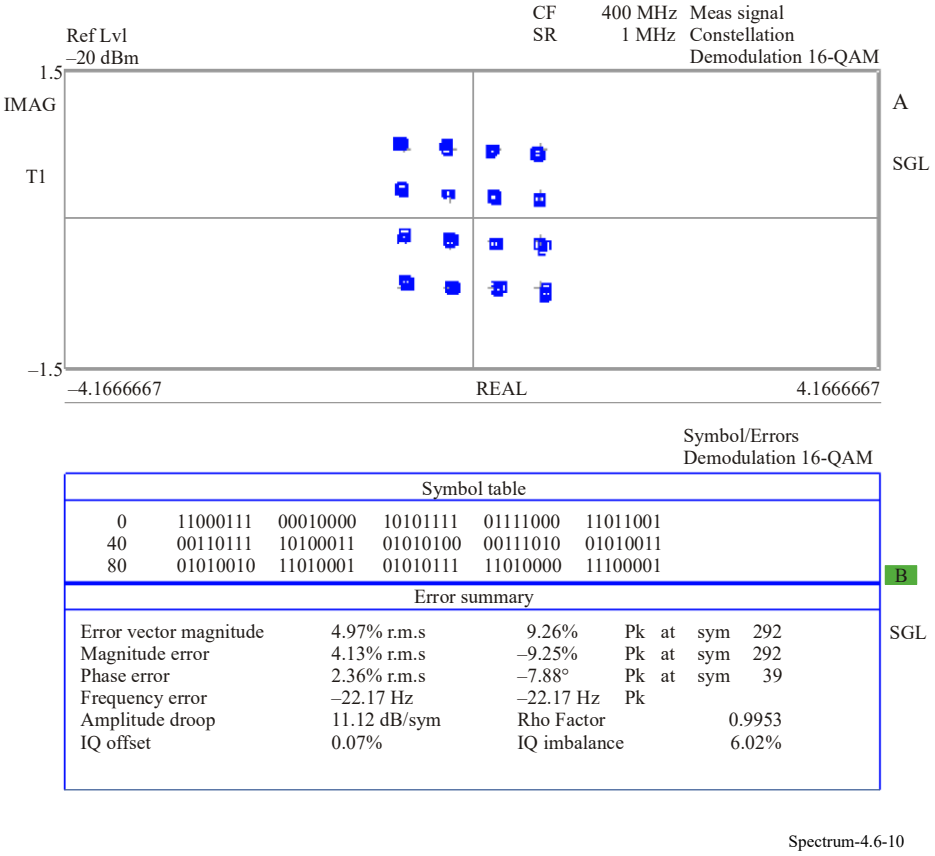
– I/Q offset.

Figure 5-43 shows the error measurement of a 16-QAM signal with considerable I/Q offset.

The sum of all these modulation errors can be expressed as the error vector magnitude (EVM). It is usually given in %.

FIGURE 5-43

Modulation error measurement example



5.6.5 Multicarrier digital modulation

Many modern digital communication systems use orthogonal frequency-division multiplex (OFDM). For OFDM signals, the following modulation parameters may be of interest:

– modulation type;

– number of carriers;

– carrier spacing;

– symbol time;

– guard interval.

5.6.5.1 Modulation type

As with single carrier systems, the modulation type cannot be determined by using standard monitoring equipment like spectrum analysers. Even most vector analysers only work with single carrier systems.

Each single carrier in the multiplex can be modulated independent of the others. That modulation can also change from one OFDM-symbol to the next. To separate the single carriers of an OFDM ensemble, specialized signal analysers are necessary. Some monitoring receivers in conjunction with suitable signal processing software may also be suitable.

They can usually display the constellation diagram either of all carriers or of selected carrier numbers only. From this display the modulation of the subcarriers may be identified.

5.6.5.2 Number of carriers and carrier spacing

Due to their modulation, the spectra of the subcarriers overlap. It is therefore difficult to visually separate them with a standard spectrum analyser.

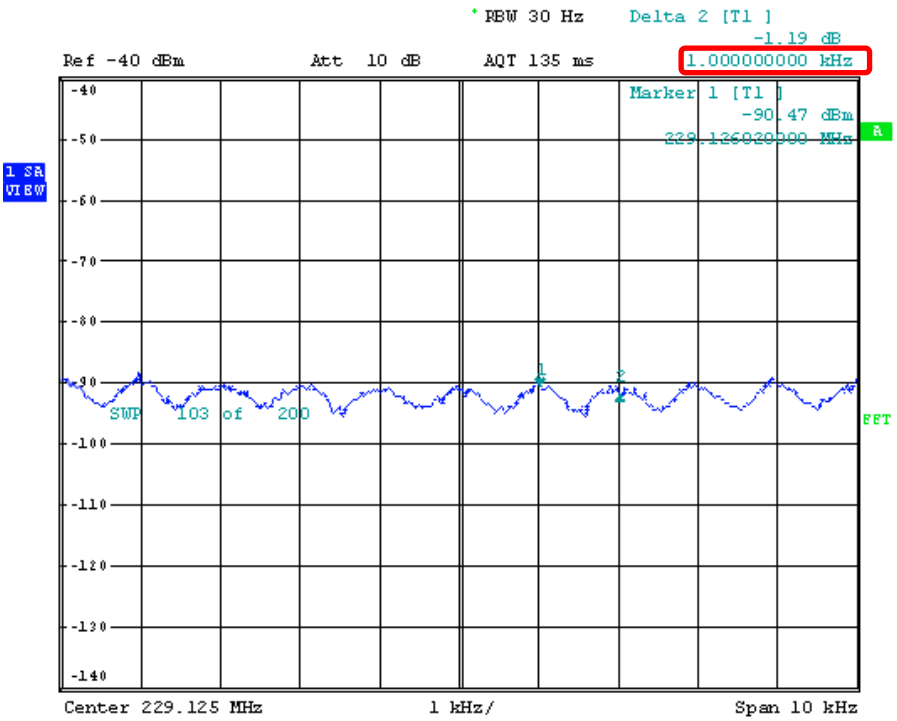
However, with a long-term trace average mode in conjunction with a narrow resolution bandwidth (RBW < 1/10 Δf), the spectrum analyser would show a picture like in Fig. 5-44.

The spectrum in Fig. 5-44 is part of a DAB signal where a carrier spacing Δf of 1 kHz can be measured, as indicated by the difference frequency of both markers in the red box.

The number of carriers can be calculated by the bandwidth between the outer carriers which is easily determined by a spectrum analyser and the carrier spacing.

FIGURE 5-44

Part of an OFDM spectrum with high resolution



5.6.5.3 Symbol time

The symbol time T_s is:

$$T_s = \frac{1}{\Delta f} \tag{5-46}$$

where Δf is the frequency separation between two neighbouring subcarriers. In the example in Fig. 5-44, the resulting symbol time would be 1 ms.

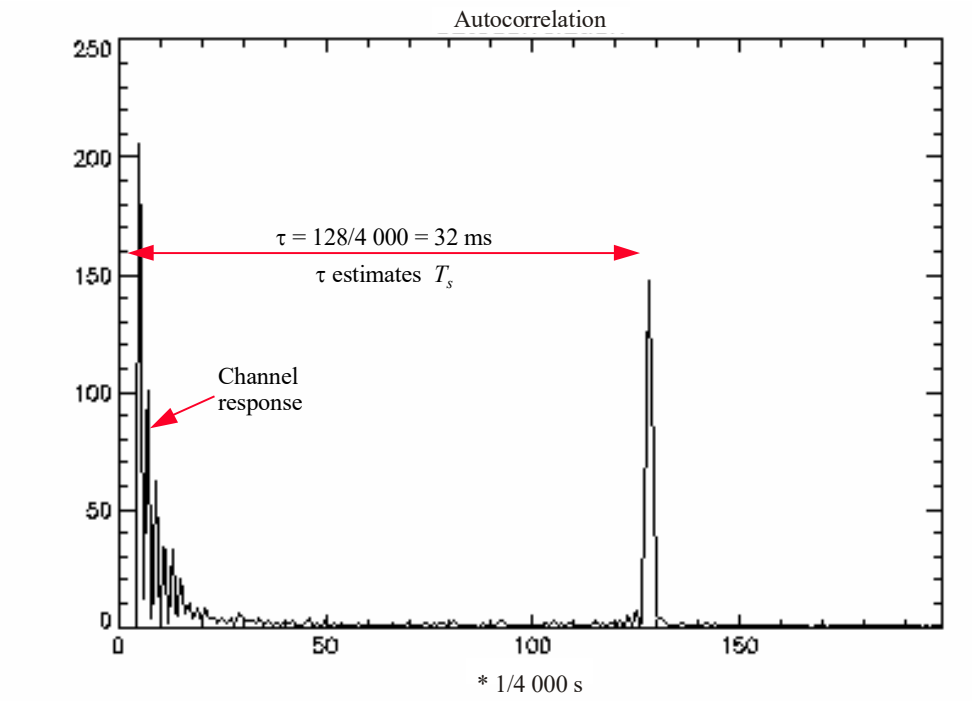
A more precise way to measure the symbol time requiring special equipment or software is to calculate an autocorrelation function of the signal's time series. The autocorrelation figure will show a peak at a time offset equal to the symbol time. An example is shown in Fig. 5-45.

One way to determine the guard interval duration T_g with this type of equipment is by performing a cyclic autocorrelation process on the signal's time series. The result will show peaks for those time intervals where some of the transmitted information repeats itself.

These times will be $T_s + T_g$. If T_s is known (or has been measured before), T_g can be calculated. Figure 5-46 shows an example.

FIGURE 5-45

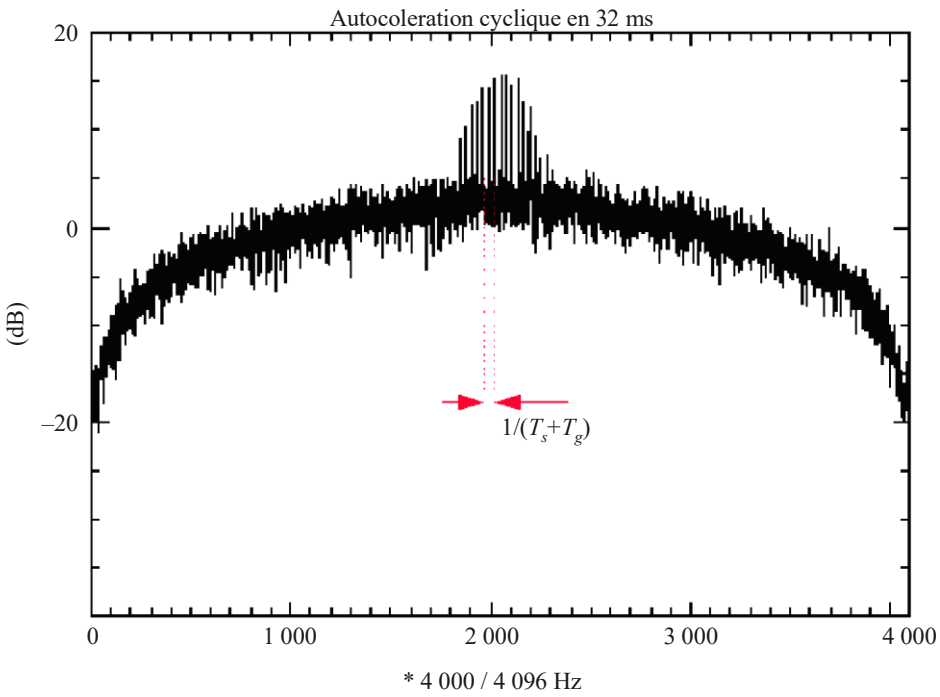
Autocorrelation of an OFDM signal



Spectrum-4.6-12

FIGURE 5-46

Cyclic autocorrelation of an OFDM time signal



Spectrum-4.6-13

5.6.6 Measurement errors

Possible sources of measurement errors are:

– an instrument bandwidth narrower than the modulated signal;

– noise or interfering co-channel signals;

– interfering signals on adjacent channels;

– reflections and multipath reception.

To avoid this problem, measurements have to be performed at the most favourable *S*/*N* ratio of the receiver (modulation meter) and using a directional antenna to eliminate as much as possible unwanted signals and obtain the maximum voltage of the wanted signal. The measurement bandwidth has to be selected in a way that it just covers the wanted signal.

Especially deviation measurements of FM signals with high AM content due to multipath propagation give erroneous results. The indicated value can be excessively high (e.g. by a factor of 2). Multipath reception must be avoided in any case when deviation measurements are performed.

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Application Note 150-1 [AN150-1] Spectrum Analyzer Amplitude and Frequency Modulation. Keysight, Santa Rosa, United States of America, downloadable at: www.keysight.com

Blue, K., *et al.* [Blue1993] Vector Signal Analyzers for Difficult Measurements on Time-Varying and Complex Modulated Signals. *Hewlett-Packard J.*, Vol. 44, p. 6-47.

Bues, D. and RIEDEL, P. [Bues1993] Planning digital radio networks using Impulse Response Analyzer PCS and test transmitter system. *News from Rohde & Schwarz*, No. 141, p. 26-27.

WOLF, J. [Wolf1993] Test receivers ESN and ESVN: Top-rounders for signal and EMI measurements. *News from Rohde & Schwarz*, No. 141, p. 11-13.

ITU-R Recommendations and Reports

NOTE – In every case the latest edition of the Recommendation or the Report is encouraged to be used.

Recommendation ITU-R BS.468 – *Measurement of audio-frequency noise voltage level in sound broadcasting*

Recommendation ITU-R SM.1268 – *Method of measuring the maximum frequency deviation of FM broadcast emissions at monitoring stations*

Report ITU-R SM.2355 – *Spectrum monitoring evolution*.

5.7 Radio direction-finding and transmitter localization

5.7.1 General considerations

The purpose of radio direction-finding (DF) is to determine the line of bearing (LoB) of any source of electromagnetic radiation by means of the propagation properties of radio waves.

Considering in this general manner, DF can be used to determine the direction towards a radio transmitter or a source of radio noise.

The use of several direction-finders (triangulation method) or direct location methods become necessary in the following cases:

– location of a transmitter in a distress situation;

– location of an unauthorised transmitter;

– location of an interfering transmitter which cannot be identified by other means;

– determination of the site of a source of harmful interference of reception, such as electrical equipment, defective insulators on a power line, etc.;

– identification of transmitters, both known and unknown.

The purpose of § 5.7 is to give a comparison of the different methods used to perform direction finding and location of an emitter.

5.7.2 Radio direction-finding

A DF is a sensor determining the direction of the arrival or azimuth (and elevation, if at HF) of an electromagnetic wave (under ideal conditions) with regard to a reference direction.

Without going into details of the phenomena involved in radio propagation, it is assumed that propagation is always along the arc of the great circle linking the radiation source to the receiving point.

In these circumstances, with appropriate receiving equipment giving the direction of the incoming wave, it is possible to take bearings of the source (transmitter and interfering current) and to know the direction of that source at the place of reception.

The functional architecture common to all (DFs) includes:

– an antenna array;

– a receiving assembly;

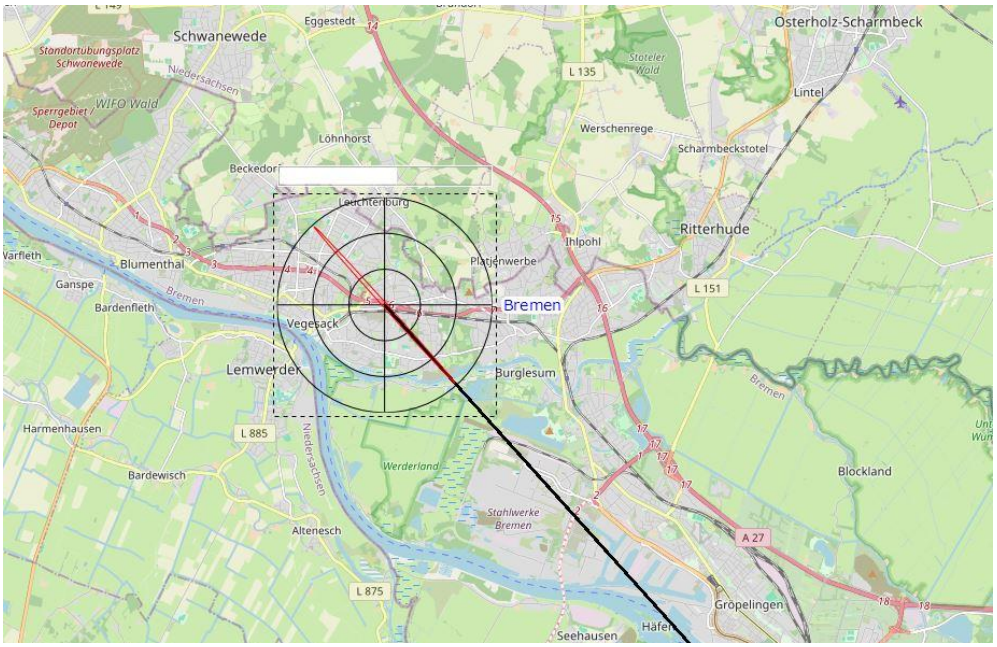
– a DF processor.

An example of the DF's display is shown in Fig. 5-47.

The elementary results should appear: angle of arrival, signal level, bearing quality, spectrum and map display.

FIGURE 5-47

An example of the direction-finder's display



5.7.2.1 Discussion of basic architecture, performance and problems

Selecting a direction-finding system is always delicate as it represents selection of a compromise on performance facing a given operational situation. There are a number of characteristic features which a direction-finder must have, irrespective of the DF principle used. The operational and design features of the equipment (mode of display, operational concept, remote-control capability, temperature range, mechanical robustness, shape, weight, power consumption, etc.) must meet the requirements of the particular application.

The main DF engineering features are:

– accuracy;

– sensitivity;

– immunity to distorted wavefronts;

– insensitiveness to depolarisation;

– effects of co-channel interference;

– resistance to receiver desensitisation;

– minimum signal duration time.

In comparison of different DF methods, such as that which follows below, only these main DF features are relevant and therefore only these will be considered here.

Typical specifications for direction finders may be found in § 3.5.

5.7.2.1.1 Accuracy

Accuracy

As to the specified accuracy, it should be noted that the system error has two components.

The first component, azimuth error, depends on the direction of incidence of the signal, siting and surrounding topography. The second component, frequency error, is a DF error as a function of the selected frequency.

The DF accuracy may be tested in a real environment, on an open-air test site or on a laboratory platform.

It should be clear that values of DF accuracy can differ considerably depending on the test environment.

The accuracy of the system can be measured according to three methods as described in Recommendation ITU-R SM.2097, Recommendation ITU-R SM.2140, Recommendation ITU-R SM.2060, Report ITU-R SM.2354:

– for fixed-site installations at the planned operational location, with a variety of modulations and using signals of the minimum *S*/*N* ratio specified by the manufacturer of the system (see Recommendation ITU-R SM.2097);

– in the planned mobile operational environment by the method described in Recommendation ITU-R SM.2140.

– at an Open air test site (OATS) which is normally defined for signals with a sufficient (> 20 dB) *S*/*N* ratio and where no reflections from nearby obstacles, ambient noise, and other radio signals may interfere with the measurement. The DF errors, which result from the propagation medium (e.g. ionosphere) and multipath effects are of course not included (see Recommendation ITU-R SM.2060);

– on a platform: the DF station without its antenna is connected to a simulator and a generator (see Report ITU-R SM.2354).

Calibration and correction

All the DF techniques must implement calibration to ensure that the required high level bearing accuracy is obtained.

Two calibration techniques may be implemented:

– Calibration of the physical structures of the DF. In order to reduce impact of mast interference, and/or resonances between antennas and/or vehicle roof interference, a calibration should be accomplished. This calibration occurs in-factory mainly for VHF/UHF DF. This is especially important when the antenna is fixed on the roof of a vehicle. However, precisely built DF antennas on top of masts without mast resonances in the frequency range of the DF antenna, and without obstacles in the vicinity of the antenna, should not need any calibration, which reduces cost and increases flexibility (e.g. spare parts do not need to be calibrated).

– Periodic calibration to correct for time and temperature drifts of each of the DF receiving channels and antenna parameters. This calibration is usually based on injection of in-phase local oscillator signals on all antenna switch inputs to equalize the channels. A double averaging method may also be used to obtain the same drift compensation without need of any periodic calibration.

Once a direction-finder has been installed, there are additional error considerations other than equipment tolerances. Errors related to siting of the DF (multipath, terrain, nearby objects, etc.), also need to be considered, and they will vary depending on site. Bearing errors caused by the surroundings should be corrected after installation in order to correct both sources of error by using known reference transmitter locations in various directions, across the frequency range of operation. Once these corrections have been established a curve can be plotted or the data stored showing. For each frequency band the correction to be applied to the direction-finder readings to obtain true bearings.

Lightning Protection

DF antennas installed on masts or at elevated sites need to be protected against direct lightning strikes by means of a lightning arrestor rod. However, electromagnetic waves that reach the DF antenna also excite the arrestor rod. In turn this generates a secondary wave that is superimposed on the primary wave. Consequently, lightning protection may have an influence on DF accuracy that depends on the design approach of the DF antenna.

Two DF antenna design approaches are established:

– The lightning arrestor rod is integrated into the design of the DF antenna and installed vertically above the antenna system as recommended in § 2.5.2.4.6. In this case, the influence of the lightning arrestor rod acts symmetrically on the DF antenna elements and tends to have a negligible impact on DF accuracy.

– The alternative design is a lightning arrestor rod that is installed in close vicinity to the DF antenna by means of a side-arm. In this case, the influence of the lightning arrestor rod is mitigated by covering major parts of the rod with ferrites combined with any necessary calibration and error correction such that it is transparent to RF signals and can achieve DF accuracies in the same range as the rod that passes through the centre of the antenna array.

If none of the above-described approaches is implemented, DF errors of more than 20°, similar to reflections in a multipath environment, are possible.

5.7.2.1.2 Sensitivity

The sensitivity of a direction-finder is a very important feature, especially in radio monitoring. Whereas in air traffic control, for instance, there is no special requirement for maximum sensitivity but rather for sufficient margin of the *S*/*N* ratio, radio monitoring is often faced with the problem of evaluating signals that are hardly detectable.

Good sensitivity is important in two aspects:

– for extending the coverage of direction-finders under good receiving conditions;

– for sufficiently reliable direction-finding under less favourable conditions.

Quite generally, the sensitivity of a direction-finder is closely linked to the duration of observation (time for averaging of several measurements) and is usually defined together with a specified bearing fluctuation (due to noise).

The variation of the sensitivity is inversely proportional to the D/λ ratio (D – diameter of DF antenna, λ – wavelength of the received signal), the *S/N* ratio, the available integration time and the selected bandwidth.

Recommendation ITU-R SM.2096 discusses sensitivity in more details and summarized procedures for measuring sensitivity.

5.7.2.1.3 Effect of multipath propagation and multiple sources

Multipath propagation

In some circumstances (urban areas or mountainous locations), severe propagation effects (mask and shadowing effects, flat and selective fading) can be observed.

Multipath phenomena are due to multiple signals coming from the same source arriving at the receiver antenna with different angles and times of arrivals due to reflection or due to diffraction during the radio propagation, as shown in Fig. 5-48.

Recommendation ITU-R SM.2061 discusses multi-path propagation in more details and summarized procedures for measuring immunity against multi-path propagation.

The effects of multiple paths for the angle-of-arrival (AOA) determination are variable:

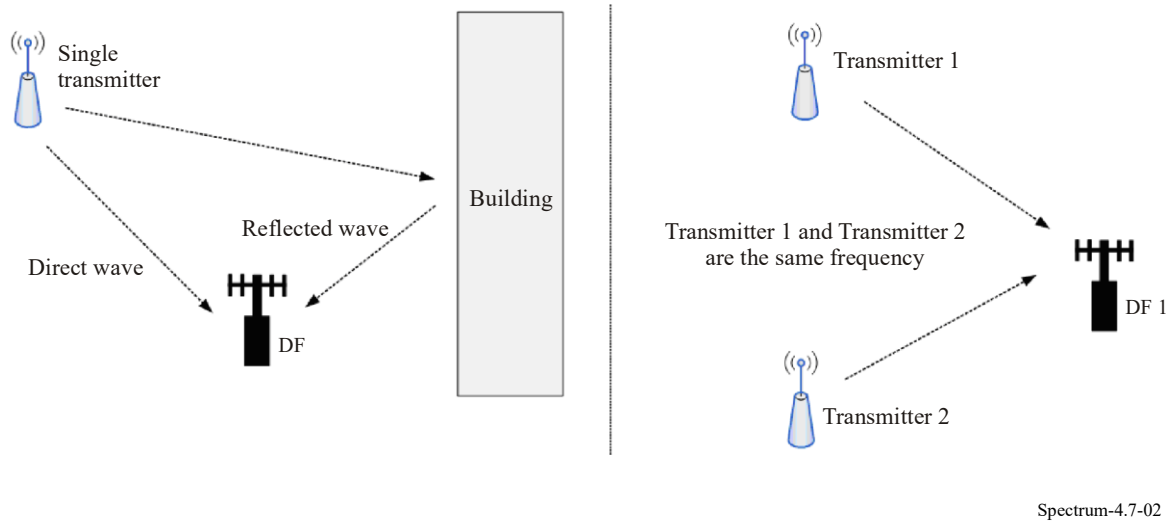
– usually, long range multiple paths (i.e. multiple paths that are caused by reflections) generate only bias in the AOA determination;

– the situation is rather different when the reflectors are close to the direction finder. If one multipath reflected by a close building or vehicle is stronger than direct one, DF result may be false. If the signal reflected by a close building or vehicle is not as strong as the direct one, DF result may be biased;

– in the right picture, signals on the same frequency arrive at the direction finder from different directions also creating a multiple source situation.

FIGURE 5-48

Example of multi-path situation (left picture) and multiple sources (right picture)



Multiple sources

A multiple source situation appears when two transmitters at different locations are using the same frequency. In such situations, AOA in combination with other methods must be adapted to the complex radio-electrical environment.

Four main cases can be observed:

1 Intra-network interference: both signals come from different transmitters that belong to the same network. Frequency re-use schemes may lead to such interference if propagation is favoured along one long path.

2 Extra-network interference: the two signals come from different communication systems.

3 The signal of interest interferes with a signal external to the network.

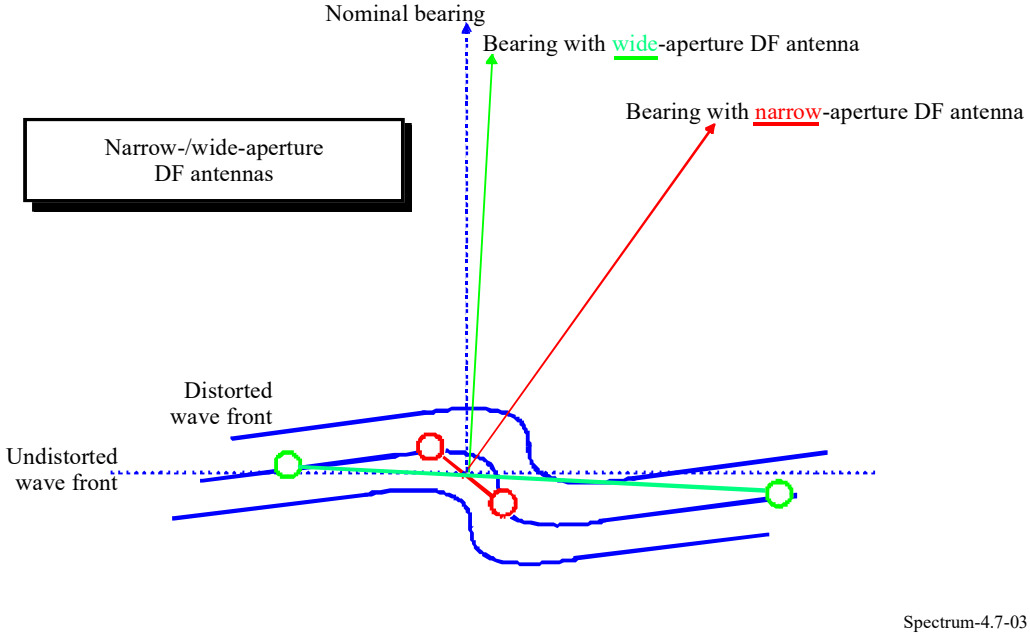
4 During digital network deployment when analogue and digital transmitters operate at the same time.

Consequences for DF techniques

Irrespective of the DF technique, each direction-finder derives its directional information from the electromagnetic field, which is generally assumed to be homogeneous, with undisturbed propagation. In this ideal case, which in fact hardly ever exists, the wave fronts are planar; the lines with equal phase and equal amplitude are parallel straight lines (see Fig. 5-49).

FIGURE 5-49

Narrow/wide aperture DF antenna



Along their propagation path electromagnetic waves are reflected by obstacles and diffracted by edges. There is also the possibility of multipath reception due to special, mostly frequency-dependent, propagation conditions. As a result, there is interference and the original planar wavefront is distorted. Different distortions result from the relationships in amplitude, phase, number and differential angle of the mutually interfering waves.

Depending on its diameter D, a DF antenna detects only a small part of the wavefront. The direction determined is always the line perpendicular to the averaged wavefront section. In a distorted field extremely different results are to be expected, depending on the DF antenna aperture relative to the spatial period of the isophase ripple in the distorted field. It is therefore advisable to choose a DF antenna with large dimensions relative to the wavelength λ to minimise the errors caused by field distortions. A ratio of $D/\lambda > 1$ refers to wide-aperture direction-finding, whereas D/λ less than 0.5 applies to narrow aperture direction-finding antenna. The intervening ratio generally applies to medium aperture direction-finders.

The capability of operating with a wide aperture is of prime importance to limit the influence of obstacles close to the DF antenna, which generate the most disturbing multipath as they can be widely spaced in azimuth from the direct path while having similar amplitudes.

5.7.2.1.4 Effect of depolarisation

Depolarisation is a shift of the polarisation plane between the DF antenna and the incident wave. The polarisation response of a direction-finder is strongly dependent on the antenna system used and consequently also on the DF method.

In this case, nearly all manpack or vehicular transmitters use vertical polarisation, for both practical and propagation reasons, and so the VHF and UHF DF antennas are often composed of vertical dipoles. In so far as the horizontal component of the receiver field is small, the error induced in direction-finding is negligible. Adaptation to horizontal polarisation is justified in the case of FM broadcast or TV transmitters or in the case of moving aircraft or helicopter direction-finding. In this case, either the direction-finder operates on the vertical component of the transmitted wave, or DF antennas matched to horizontal polarisation can be used.

5.7.2.1.5 Minimum signal duration

Depending on the operating principle of a direction-finder, the signal must be available for a certain minimum time to allow bearings to be taken. Signal duration less than 1 ms are achievable with narrow and broadband receivers.

This performance mainly depends on the DF techniques and on the signal processing capabilities of the equipment.

5.7.2.2 Different DF techniques

Selecting a DF system for one specific application is typically a matter of combining features in antenna, receiver and processor design in some optimum arrangement. Radio direction-finding techniques have traditionally been divided into three basic approaches: amplitude sensing systems, phase sensing systems, and systems that sense both amplitude and phase. Many modern DFs employ combinations of phase and amplitude sensing techniques. This section compares a sampling of DF techniques in a simplified overview and illustrates the differences in the most popular methods. A comprehensive discussion of the theory of operation for each of these techniques is beyond the scope of this Handbook. Those readers who desire a more technical explanation are referred to texts on DF techniques.

Modern DF techniques are:

– rotating antenna;

– Doppler and pseudo-Doppler;

– Adcock/Watson-Watt;

– phase interferometer;

– correlative interferometer;

– advanced resolution.

Each technique is examined in terms of performance factors and highlighted in terms of its unique features.

5.7.2.2.1 Rotating antenna

A very simple way of detecting the angle of arrival of a signal (AOA) is the use of a rotating antenna/antenna system.

For frequencies below 30 MHz, a loop antenna can be manually rotated to steer a null in the direction of arrival.

For higher frequencies, a remote-controlled antenna and receiver can be used to show the input level of the receiver as a function of angle. A vertically or horizontally polarised directional antenna can be used. In Fig. 5-50 (top), a full turn of the receive antenna was made while the levels were recorded as a function of the antenna angle. The diagrams are normalized to make the highest level hit the grey border of the circle. In the top image, a single, directed antenna was used to do the scan. It can be seen that the maximum levels show a broad range of angles. The minimum levels show a sharper dip in the pattern and thus allow a better estimate of the receive direction. To improve the bearing result an antenna system of two identical antennas that provides the sum or the difference of the input levels of the two antennas can be used. The difference results in a very sharp minimum when the antennas are pointed in direction to the transmitter. The summing signal has a higher sensitivity but the directivity is much lower, see Fig. 5-50 (bottom).

This direction-finding method can be used for all transmissions which are longer on air than the equipment needs for two revolutions of the antenna system. This method also proved its usability in radio systems using more than one transmitter on the same frequency like DVB-T, TETRA, GSM, etc.

Fast rotating antenna systems may have a rotating speed up to 200 r.p.m whereas slow ones need more than 1 min for a whole circle. The received polarization depends only on the antenna mounting.

Another advantage of this method compared to others is that it can be used for vertically and horizontally polarised signals.

The lower frequency limit is determined by the mechanical dimensions of the antenna and will usually not be below 80 MHz. The upper frequency is mainly limited by the specification of the swivel coupler between the mast and the antenna. So called spinning antennas are available for frequencies up to 40 GHz.

FIGURE 5-50

Receive level after a full turn of the receive antenna: top: single directed antenna; bottom: coupled antennas, showing antenna pattern – a) Sum, b) Difference, c) Difference displayed in a map

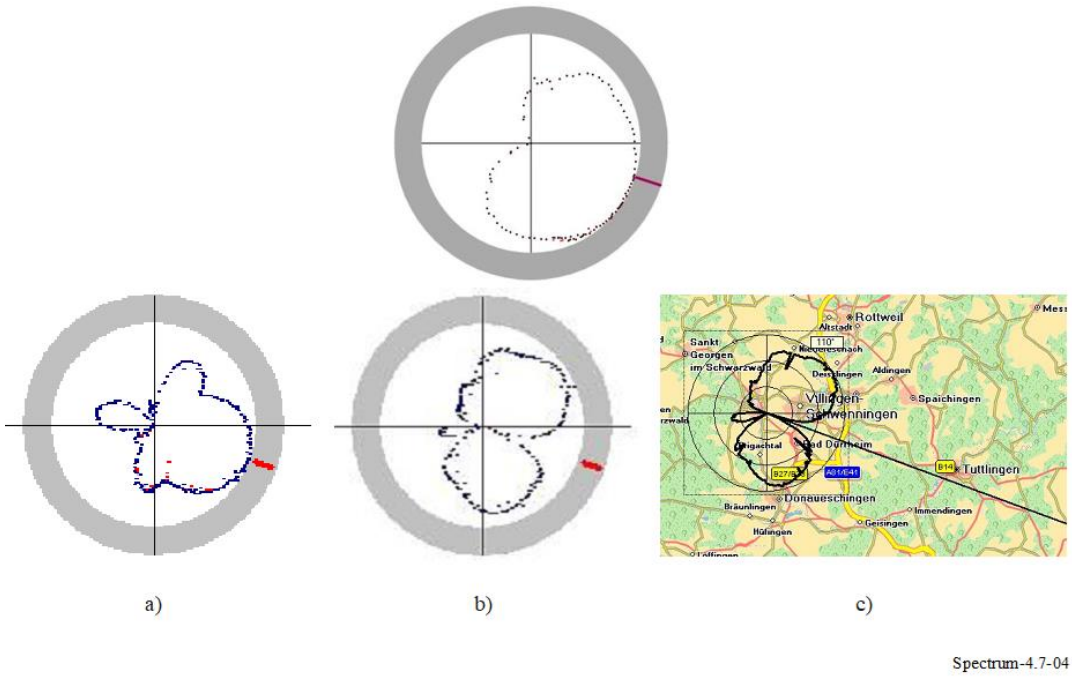


TABLE 5-11

Examples of installations

Frequency range	Polarization	Antenna coupling	Rotating speed
80-1 000 MHz	Vertical, horizontal	sum, difference	60 r.p.m
80-1 300 MHz	Vertical	sum, difference	1 r.p.m
500 MHz – 40 GHz	45°	sum, difference	≤ 200 r.p.m

5.7.2.2.2 Doppler and pseudo-Doppler

Doppler and pseudo-Doppler were developed in the 1950s, by studying the Doppler shift imparted by a moving antenna on a received signal. The rate of mechanical rotation for the direct Doppler principle is generally impractical at frequencies below the UHF band, so an electronic switching method was developed to simulate the antenna rotation scheme with a fixed, circular array. This technique is known as the pseudo-Doppler method.

To obtain unambiguous DF results, the spacing between the individual antenna elements must be less than half of the operating wavelength, in practical installations one third of the wavelength is selected.

DF systems using (pseudo-) Doppler technology have a good sensitivity combined with a good immunity against multipath propagation compared to Adcock or Watson-Watt methods.

5.7.2.2.3 Adcock/Watson Watt

Adcock/Watson-Watt (WW) systems (see Table 5-12) exploited improvements in antenna and signal processing to provide a system with a near-instantaneous readout.

The Adcock antenna array used in these systems (developed in 1918) is comprised of dipole or monopole antenna pairs combined through a 180° hybrid circuit to exhibit the familiar “figure of eight” reception pattern seen in a loop antenna.

Two Adcock pairs, arranged on orthogonal baselines, exhibit a response to the signal direction of arrival, which varies with the sine of the direction of arrival at one antenna, and varies with the cosine of the direction of arrival at the second antenna.

The Watson-Watt DF technique employs three phase-matched receivers and displays the angle of arrival, in terms of the sine and cosine functions and a third, omnidirectional channel to solve the ambiguity problem.

Modern Watson-Watt direction finders use DSP techniques for calculating the bearing.

FIGURE 5-51

Principle of Watson-Watt DF system

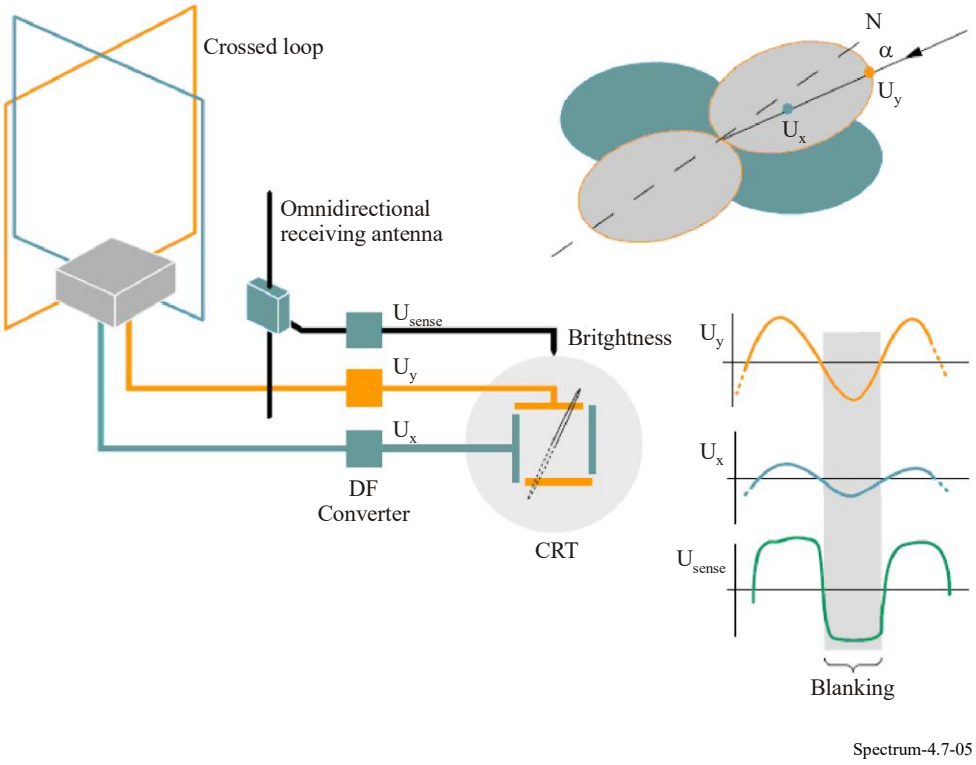


TABLE 5-12

Adcock/Watson-Watt DF systems

DF antenna array measurements	Amplitude measurements are performed at the output from three antennas. Antennas configured to respond with the signal angle of arrival in sine, cosine, and omnidirectional patterns. Synchronous amplitude measurements made, typically using three coherent receiver channels.
Measurement conversion to DF bearing	Bearing = arctan (sin θ/cos θ); this calculation is sometimes refined by factors from a calibration table. Ambiguity problem solved by (omnidirectional) sense channel.
Accuracy (without site influence)	1° to 2° r.m.s.
Sensitivity	Med-High. Performance based on antenna selection.
Minimum signal duration	1 ms, the bearing is indicated without delay.
Immunity against depolarisation	When using highly balanced antennas, bearing errors are low for depolarisation < 45°; depolarisation compensation algorithms cannot be used.

TABLE 5-12 (*end*)

Immunity against distorted wavefronts (coherent interference)	Limited, as no wide aperture antenna arrays possible.
Immunity against co-channel interference (non-coherent interference)	Separation possible using analogues CRT display techniques. Operator interpretation of CRT used in resolving interference pattern. Digital signal processing cannot algorithmically separate time coincident co-channel signals. Histogram techniques may be employed for non-time coincident signals.
HF skywave capability	Cannot determine elevation angle for skywave signals; can maintain good sensitivity for high angle signals. Crossed-loop antenna may be used in applications where extremely high angles of arrival are of interest.
Remarks	These systems have the advantage of more than 50 years development and represent the most successful early DF techniques; they retain relevance in part due to the very short system minimum signal duration time and their ability to measure the bearing to the source of transient signals (including lightning for which they were originally developed).

5.7.2.2.4 Phase interferometer

Interferometer methods (see Table 5-13) were developed in the 1950s and 1960s as a means for very accurate, instantaneous LoB measurement. This system uses a differential phase measurement between at least two independent antennas. The critical element of this type of system is the phase detector, which returns an estimate of the phase delay between the two received signals.

Using this delay, an angle of arrival can be estimated. Combinations of 3, 4, 5 or more antennas can be used to obtain a 360° field of view, without rotating the antenna. Triangular installations are useful below 30 MHz, at higher frequency ranges circular arrays are preferred.

Multi-channel receiving systems and antenna switching have been used successfully as a means of measuring inputs from several antennas.

Figure 5-52 shows the phase difference when an incident wavefront arrives with an angle θ on two antennas, separated by a distance “d”.

FIGURE 5-52

Phase interferometer: phase difference principle

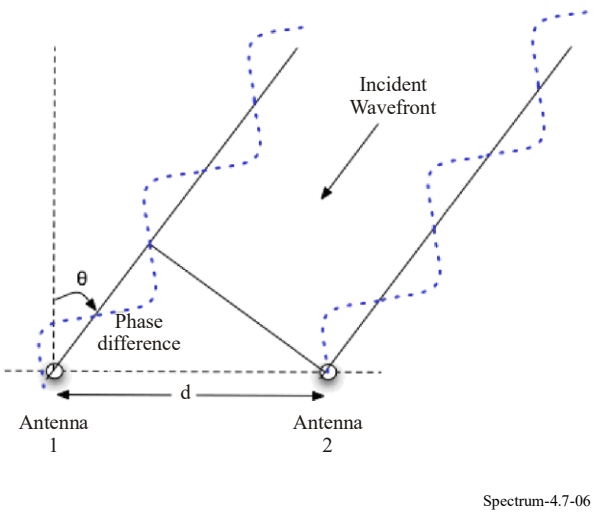


TABLE 5-13

Phase interferometer

DF antenna array measurements	Differential phase measurements between a subset of the possible pairs of antennas within the antenna array. For more details, refer to § 3.5.4 – Number of receivers.
Measurement conversion to DF bearing	Bearing calculated by combining information about the antenna array with differential phase measurements obtained for pairs of antennas in the array. Phase measurements for a specific pair can be used to compute an angle of arrival, based on knowledge of the antenna spacing. Using knowledge about the array geometry, measurements from several pairs may be combined to resolve ambiguities in azimuth, and to calculate the elevation angle of arrival.
Accuracy (without site influence)	≤ 1° r.m.s.
Sensitivity	High
Minimum signal duration	10 ms 1 ms* * systems which use antenna switching to a pair of coherent measurement channels, are common. Minimum signal duration can be shorter if one receiver is used for each antenna element and all measurements are made in parallel.
Immunity against depolarisation	Function of antenna element polarisation linearity only since polarisation compensation algorithms cannot be used; typical depolarisation errors are low for polarisation slant up to 60° and become large for greater polarisation slant.
Immunity against distorted wavefronts (coherent interference)	High when using wide aperture antenna arrays.
Immunity against co-channel interference (non-coherent interference)	Separation possible using histogram techniques for non-time coincident signals; for time coincident signals only the signal that is stronger by 3 to 5 dB can be evaluated.
HF skywave capability	Can also determine elevation angle for skywave signals; can maintain good sensitivity for high angle signals when the antenna array consists of crossed-loop antennas.
Remarks	Phase interferometers are compatible with modern digital signal processing techniques; there are a number of systems now on the market that use personal computers to perform the DF processing; they are not constrained to using circularly disposed antenna array systems.

5.7.2.2.5 Correlative interferometer

The correlative interferometer uses phase and amplitude information of the signal.

Typically, these systems estimate the LoB for the resolved signals, by correlating the received amplitude and phase data to an amplitude and phase calibration database for the antenna array.

The basic elements of the correlation-based systems are as follows:

1 Antenna array

- A signal is received simultaneously by multiple antennas in an array (most likely circular array to provide omnidirectional overage).
- Each antenna measures the complex voltage (which include amplitude and phase) of the incoming signal.

2 Reference table

- The reference table contains information about the amplitude and / or phase from every antenna element, for every possible direction of arrival (in azimuth as well as elevation) for the receive frequency of interest. Typically, it is calculated after the user tunes the direction finder to a new receive frequency.
- In the case that the direction-finding antenna is mounted close to conductive structures, for example on board of ships or aircraft, the reference table may be created by calibration. In this case, the test signal is transmitted from every possible direction and the information about amplitude and / or phase is measured for every direction and receive frequency of interest.

3 Comparison stage

- The system compares the incoming signal's measured data with all reference patterns in the database.
- The comparison is performed by calculating the quadratic error of the correlation coefficient.
- It computes a correlation coefficient for each direction, basically measuring how similar the incoming signal is to each reference direction.

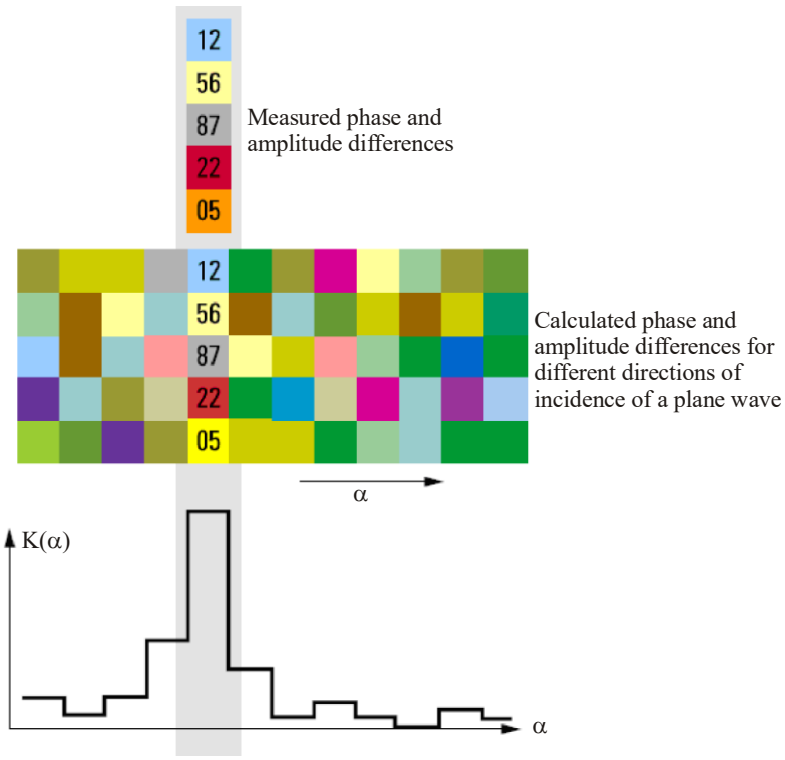
4 Direction estimation

- The system selects the direction with the highest correlation, which is the best match for the observed data.
- If the correlation is made for the different azimuth values of the reference data set, the bearing is obtained from the data for which the correlation coefficient is at the maximum.
- The direction is reported as the LoB of the signal.

This is shown in Fig. 5-53. This method is capable of eliminating instrument and site-related errors and can be adapted for use with a wide variety of antenna arrays.

FIGURE 5-53

Principle of correlative Interferometer



Spectrum-4.7-07

TABLE 5-14

Correlative interferometer

DF antenna array measurements	The complex signal voltage (amplitude and phase) is measured for each antenna, with measurements made on at least two antennas at a time. For more details, refer to § 3.5.4 – Number of receivers.
Measurement conversion to DF bearing	Correlative interferometer uses calibration vectors generated during factory calibration of the system. The bearing is the interpolated azimuth value that corresponds to the azimuth calibration vector that best matches the measurement vector.
Accuracy (without site influence)	≤ 1° r.m.s.
Sensitivity	High
Minimum signal duration	for HF 10 ms for VHF/UHF 1 ms System processing times will be lengthened if less parallel receiver channels are used than the number of antenna elements.
Immunity against depolarisation	Function of antenna array polarisation characteristics unless using the dual polarised algorithmic compensation suitable with these vector processing systems.
Immunity against distorted wavefronts (coherent interference)	High when using wide aperture antenna arrays.
Immunity against co-channel interference (non-coherent interference)	Separation possible using histogram techniques for non-time coincident signals; for time coincident signals in the vector correlation system, only the signal that is stronger by 3 to 5 dB can be evaluated.
HF skywave capability	Can also determine elevation angle for skywave signals; can maintain good sensitivity for high angle signals when the antenna array consists of crossed-loop antennas.
Remarks	These DF techniques are compatible with the new generation digital signal processing; co-processors operating in the new generation personal computers have sufficient processing power to perform these calculations rapidly.

5.7.2.2.6 Advanced resolution techniques

Advanced resolution techniques are often referred to as super and high resolution. These techniques are used to discriminate among signals (either multiple paths or multiple sources) arising from several transmitters at the same frequency.

Two techniques are discussed in this section:

– beam forming and space matched filter (e.g. CAPON algorithm**):** a steering antenna array beams in all direction and the algorithm looks for peaks in the input power. The computation of the beam forming and space matched filter algorithm is based on an expression of the steering vector while attempting to minimise the power contributed by noise and interferer signals;

– subspace techniques: they are based on the cancellation of the noise, of interference signals and multipath. The computation of the subspace techniques algorithm is based on a principal component (or eigenvalue) analysis of the data samples of all sensors. The wave incident angles are computed by varying the steering vector and looking for angles were the steering vector is orthogonal to the eigenvectors that corresponds to the noise eigenvalues.

The MUSIC technique as an example of subspace techniques:

MUSIC (Multiple Signal Classification) is an algorithm in signal processing for determining the Angle of Arrival (AOA) of multiple signals impinging on an array of antennas. It's particularly valued for its ability to provide high-resolution results, as long as the number of incoming signals doesn't exceed the number of sensors in the array. Typical applications include:

– Radar systems for target tracking

– Wireless communications to enhance signal reception

– Sonar systems for underwater navigation and detection

The main idea behind MUSIC is to separate the signal space from the noise space in such a way that the directions of arrival of the signals can be accurately determined. This separation is done by decomposing the covariance matrix of the signals received at the antenna array into two parts:

1 Signal Subspace: Contains the useful signal information.

2 Noise Subspace: Contains only noise.

By analysing the noise subspace, MUSIC identifies the angles where signals are coming from, since the noise is orthogonal to the signal subspace at these angles.

MUSIC DF Algorithm calculation steps:

1 Antenna Array Setup: The system begins with an array of antennas (generally linear or circular), each receiving signals from various directions. The goal is to determine the angles at which these signals arrive. When the MUSIC algorithm is applied in conjunction with a circularly symmetric array, it enhances the system's ability to estimate the directions of multiple signals, even when they are closely spaced in angle.

2 Covariance Matrix Calculation: The algorithm forms the covariance matrix based on the signals received by the antenna array. This matrix contains information about the correlation between signals at different antennas.

3 Eigenvalue Decomposition: The covariance matrix is decomposed into its eigenvalues and eigenvectors. These eigenvectors are then used to form the signal subspace and noise subspace.

4 Form the MUSIC Spectrum: MUSIC computes a pseudo-spectrum function that evaluates how well different angles match the noise subspace. For every possible angle (or direction), the algorithm checks whether the noise subspace is orthogonal to the steering vector (which represents the hypothetical signal arriving from that angle).

5 Peak Detection: The angles corresponding to peaks in the pseudo-spectrum indicate the directions of arrival of the incoming signals. These peaks occur because the noise is orthogonal to the signal subspace at the correct AOA angles.

Advantages of the MUSIC DF method:

1 High Resolution: MUSIC can distinguish between signals even when they are very close in angle, making it highly accurate for direction finding.

2 Works with Multiple Signals: It can estimate the AOA of multiple signals simultaneously.

3 Flexibility: MUSIC works for different kinds of arrays, which makes it adaptable to various practical applications. However, circular or linear arrays are used in most applications.

Disadvantages of the MUSIC DF method:

While the MUSIC (Multiple Signal Classification) algorithm offers high-resolution direction finding (DF) capabilities, it does have several limitations:

1 Computational Complexity:

MUSIC requires eigenvalue decomposition of the covariance matrix, which can be computationally expensive, especially for large antenna arrays or when processing a large number of snapshots. This makes it less suitable for real-time applications with limited processing power.

2 Sensitivity to Model Errors:

The algorithm assumes that the signals arriving at the array follow a well-defined model (e.g. plane wave propagation). Any deviations from this model, such as sensor errors, array calibration issues, or signal distortion, can lead to inaccurate results or degraded performance.

3 Underestimation and overestimation of the number of interference source:

When the estimated number of interferers matches the actual number, the MUSIC algorithm accurately estimates the directions of interference. However, if there is overestimation, the algorithm may produce false peaks in the spectrum. In the case of underestimation, the signal subspace shrinks, causing some peaks to disappear.

4 Does Not Handle Coherent Signals Well:

When interference sources are coherent, the MUSIC algorithm struggles to estimate the number of interferers because it cannot separate the signal and noise subspaces, preventing spatial spectrum estimation.

TABLE 5-15

Advanced resolution

DF antenna array measurements	The complex signal voltage (amplitude and phase) is measured for each antenna, with measurements made on at least two antennas at a time. In practice a minimum of two coherent receiver channels is required. For the subspace technique, voltage pairs for all possible antenna pairings in the antenna array are used to generate what is known mathematically as a measurement "covariance matrix." The matrix is evaluated to resolve co-channel content in the received signal.
Measurement conversion to DF bearing	Multiple bearings are calculated by using interpolated azimuth values. The antenna array being fixed, each of these values corresponds to a calibrated spatial signature. The calibrated spatial signature that best matches the sources signatures provides the azimuths estimation of the sources.
Accuracy (without site influence)	≤ 1° r.m.s.
Sensitivity	High Sensitivity depends on the selected method. Using the subspace technique performs better on signals with low signal-to-noise ratio compared to beamforming technique.
Minimum signal duration	for HF 100 ms for VHF/UHF 10 ms System processing times will be substantially lengthened if less parallel receiver channels are used than the number of antenna elements. The signal needs to be stable over the entire measurement period, which is difficult with less receivers than antenna elements, particularly at HF. Therefore, the same number of receivers as antenna (N-channel receivers) are generally used in these systems.
Immunity against depolarisation	Function of antenna array polarisation characteristics unless using the dual polarised algorithmic compensation suitable with these vector processing systems.
Immunity against distorted wavefronts (coherent interference)	Beamforming techniques can separate multiple uncorrelated interferers but not coherent interferers. Subspace techniques can separate multiple uncorrelated interferers and partly coherent interferers. Both techniques have improved performances when using wide aperture antenna arrays.
Immunity against non-coherent interference	Both techniques can separate non-coherent interferers.
HF skywave capability	Can also determine elevation angle for skywave signals; can maintain good sensitivity for high angle signals when the antenna array consists of crossed-loop antennas.
Remarks	These DF techniques are compatible with the latest generation of digital processing; that has sufficient processing power to perform these calculations rapidly; these systems are not constrained to requiring circularly disposed antenna arrays.

5.7.2.2.7 Comparison of AOA techniques

This section compares the various methods and identifies which method is the most effective in dealing with multipath and multiple-source situations.

Table 5-16 compares the main AOA estimation algorithms. It summarizes the main performance and use of these methods.

TABLE 5-16

Summary comparison of DF techniques

Accuracy/Angle separation	Sensitivity	Immunity to multipath	Minimum signal duration	Remarks
Rotating antenna				
2° to 5° r.m.s. Depending on the used antenna system	High	Good	Depending on the rotating speed, up to 1 min	Simple implementation Real time method Good separation of multisource signals
Adcock/WW methods				
1° to 2° r.m.s. No angle separation	Medium to high	Limited	1 ms	Simple implementation Real time method Operational and widely implemented method
Phase interferometer				
Usual accuracy 1° r.m.s. for a single source Angle separation can be good if time and frequency resolution is high	High	Medium to good for single source, depending on antenna aperture	10 ms 1 ms (Note 1)	Simple implementation Real time method Operational and widely implemented method
Correlative interferometer				
Usual accuracy 1° r.m.s. for a single source Angle separation can be good if time and frequency resolution is high	High	Medium to good for single source, depending on antenna aperture	HF: 10 ms VHF/UHF: 1 ms Depends on number of antenna elements and receivers as well as processing speed	Moderately complex implementation Operational and widely implemented method
Space matched filter – (CAPON)				
Good for uncorrelated sources. Usual accuracy reaches 2° Processes usually 2 to 3 uncorrelated sources that are angle separated	High	Processes partly coherent radio environments Robust to multiple uncorrelated sources. Cannot process correlated multipath signals	HF: 100 ms VHF/UHF: 10 ms Depends on number of antenna elements and receivers as well as processing speed	Moderately complex implementation if off-line analysis. Complex implementation requiring more computing resources if real time. Requires long integration time to achieve results, during which time the signal environment should be relatively stable

TABLE 5-16 (*end*)

Accuracy/Angle separation	Sensitivity	Immunity to multipath	Minimum signal duration	Remarks
Subspace method (MUSIC)				
High accuracy performance < 1° Can resolve up to (*N*-1) independent sources and usually [(*N*/2-1)] for partly-coherent sources, where N is the number of antenna elements (typically: 5…8). Limited only by calibration errors and integration duration	High	Processes usually around [(*N*/2-1)] partly-coherent sources. Robust to multiple partly-coherent sources or multiple paths and to noise (processes efficiently *S*/*N* ratios < 0). Cannot process correlated multipath signals	HF: 100 ms VHF/UHF: 10 ms	Moderately complex implementation if off-line analysis. Complex implementation requiring significantly more computing resources if real time. Operational for adverse radio environments (urban, mountainous). Requires long integration time to achieve results, during which time the signal environment should be relatively stable

NOTE 1 – Successful systems, which use antenna switching to a pair of coherent measurement channels, are common. The minimum signal duration is shorter when one receiver is used for each antenna and all measurements are made in parallel.

5.7.2.2.8 Combined direction finding techniques

Space match filter and subspace DF method and techniques may be helpful in severe radio environments. It is desirable to have a real-time implementation of these DF methods but this may lead to complex systems, involving an N-channel system with one receiver, processing and recording channel for each antenna element.

To solve this issue, multi-channel equipment implementing a real-time treatment based on a simple algorithm may be associated to a multichannel digital recording system to cope with the more difficult radio-environments in batch mode (some tens of seconds).

It will then be possible for the system to adapt itself to the environment by applying several AOA methods of increasing complexity:

1 A correlative interferometer or a vectorial correlation allows a fast and real-time scanning of the radio environment to give a first location of the dominant emitters or sources, as well as a first indication of presence of interferences sources.

2 An advanced resolution method will give a sufficient discrimination/location for the environments of average complexity and\or the needs of limited precision.

Other techniques, using FFT analysis, may also work in complex signal environments.

5.7.2.3 Influence of the environment

5.7.2.3.1 Accuracy of bearings of DF below 30 MHz

Recommendation ITU-R SM.854 classifies bearings into four classes based on accuracy and observational characteristics:

Class A – Probability of less than 5% that error exceeds 2°.

Class B – Probability of less than 5% that error exceeds 5°.

Class C – Probability of less than 5% that error exceeds 10°.

Class D – Bearing with an error greater than those in Class C.

Recommendation ITU-R SM.854 also recommends that administrations provide statistical data to support assigning numerical averaging values to the observational characteristics, e.g. standard deviation, number of samples, actual error, statistical processing of the sample.

5.7.2.3.1.1 Errors caused by the ionosphere

Direction-finders operating below 30 MHz are susceptible to errors induced by reflections of transmissions from the ionosphere. Specialized systems exist for operating in these conditions, if required. These systems are typically associated with long-range, over-the-horizon signal-locating operations. Not every station in a spectrum monitoring system requires this capability.

The ionosphere is an inhomogeneous medium, which is subject to continuous changes.

In practice, propagation between transmitter and receiver may involve different modes, including a ground wave, and single or multiple reflections on E and F layers.

The electromagnetic field intercepted by the antenna array of the direction-finder may be considerably distorted by interference of the multipath rays, thus causing scatter and errors in the bearings measured. Using proper polarisation diversity and algorithms may reduce these.

The reception of transmissions with *one* or *multiple* reflections at the ionosphere thereby leads to different consequences:

– horizontal stratification;

– ion density;

– structure (consists of undulations of varying sizes with up to 2 km deep and several hundred kilometres long);

– fine structure (leads to scattering effects in reflection);

– depolarisation (contra-polarised signals – circular or elliptical – as a result of reflection).

In cases of one single reflection, a relatively slow variation in the bearing will be superimposed the rapid fluctuations caused by scattering from the "fine structure" of the ionosphere. The accuracy of the bearing also depends on the angle of inclination relative to the reflecting surface. For this reason, errors in the bearings increase with the height and the number of reflections and they also increase with decreasing transmitter distance.

In cases of multiple reflections, observation is made difficult by the fact that scatter occurs at one or more points on the ground where the wave is reflected. Because of the scatter due to the fine structure of the ionosphere, the angle at which the wave is received is not constant but is contained within a cone with its vertex at the centre of the antenna array.

The scatter, which takes place at the point of reflection on the ground increases the angle of aperture of this cone and thus increases the amplitude of the rapid fluctuations of the bearing.

5.7.2.3.1.2 Errors due to siting

Section 2.5.1.3 gives information on the siting of a direction-finding station.

The site must be selected with great care to minimise errors due to wave-front distortion caused by sudden changes in ground conductivity or re-radiation from obstacles.

Since actual sites will not be ideal, the nature of the site and the characteristics of the adjacent terrain are bound to introduce errors, which will vary with direction and frequency.

These errors can be corrected by calibrating the installed DF using multiple reference transmitters in known directions across different frequencies (see § 5.7.2.1.1, Accuracy).

5.7.2.3.2 Accuracy of bearings of DF above 30 MHz

Recommendation ITU-R SM.854 classifies bearings into four classes based on accuracy and observational characteristics. It should be noted that the values for the various classes differs from those below 30 MHz.

Class A – Probability of less than 5% that error exceeds 1°.

Class B – Probability of less than 5% that error exceeds 2°.

Class C – Probability of less than 5% that error exceeds 5°.

Class D – Bearing with an error greater than those in Class C.

Bearings obtained with a direction-finder operating above 30 MHz are subject to errors due to:

– equipment (or technique used by the equipment);

– site of the direction-finder;

– propagation.

Errors due to the equipment result from its design and manufacture.

Errors due to the site arise from irregularities in the configuration or composition of the terrain in the vicinity of the direction-finder. These errors vary with direction and frequency. They may thus be regarded as variable errors.

The third type of error is due to irregularities in propagation. These may give rise to side deviations in the direction of propagation relative to the direction of the arc of the great circle between the transmitter and the direction-finder. Moreover, irregularities in propagation give rise to errors due to polarisation.

5.7.2.4 Remote control networking for DF stations

A remotely controllable direction-finder network can offer advantages of both economy of operation and flexibility of use. Remote control of computerised systems is covered in §§ 2.5 and 3.6.3.

5.7.3 Location

In many cases, the line of bearing will not be sufficient for identification and the exact position of the transmitter will be required. Four main methods are used to identify a location:

1 the classical method: to combine two or more DF-delivering AOA (Angle of Arrival) results in order to perform multi-angulations (manually or by computer);

2 the time difference of arrival (TDOA) method;

3 the homing or standalone method by using a mobile direction finder;

4 the Single Station Location (SSL) in the HF range relying on ionospheric propagation: it is possible to determine the position of a transmitter with only one DF station which also delivers the AOA elevation information in addition to its azimuth.

A combination of more than one of the above methods can provide better location results than one of the methods by itself. For example, a hybrid approach combining AOA and TDOA to obtain location information is often better than either of these methods alone.

The following sections give details about each of these location methods.

5.7.3.1 Triangulation and multi-angulation methods of location

The triangulation method, which is a particular case, is described hereafter.

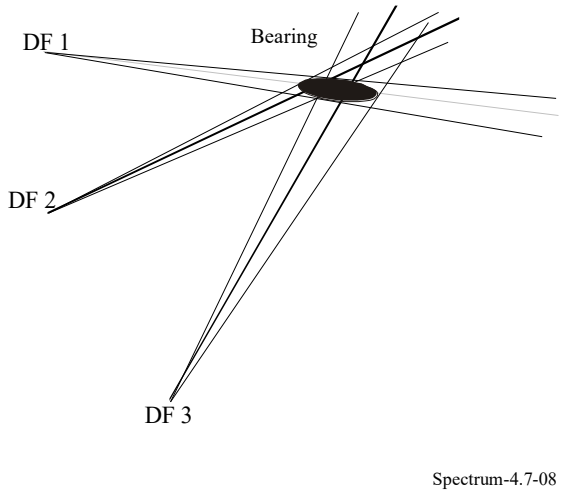
5.7.3.1.1 General

The triangulation method requires a minimum of two and preferably three LoB results. The intersection of LoB determines the emitter location. Due to measurement errors of the directions finders, the result is an ellipse, which represents the possible location of the transmitter, see Fig. 5-54.

The better the DF accuracy and the more orthogonal the bearings are the smaller is the area of uncertainty.

FIGURE 5-54

Location using triangulation method



The location calculation is directly dependent on the quality of bearings of the various direction-finding stations. To attain a sufficient quality, bearings should be analysed on each step in the localization process, that is, in monitoring/DF stations and at the location centre where the location (fix) is actually computed.

At monitoring/ DF stations, a manual analysis mainly consists of:

– checking for correspondence between a locally heard signal and a signal of interest for the monitoring station;

– classifying the bearings in case of the presence of more than one signal on the same frequency (interference);

– eliminating obviously aberrant bearings;

– calculating the mean value of bearings;

– calculating the variance of bearings.

At the location centre, the analysis of bearings mainly consists of:

– determining the bearings to be used for the location calculation;

– calculating the position of the probable transmission point;

– calculating the uncertainty ellipse.

In manually operated localization systems, the quality of bearings is highly dependent on the operator's skill in performing such an analysis. In automatically operated localization systems, the analysis is performed solely by the means of software.

5.7.3.1.2 Features of the location depending on frequency

Below 30 MHz

Below 30 MHz, in addition to ground waves, waves can also propagate by single or multiple reflections and ducting in the ionosphere.

The signal received by a direction-finder is a composite signal originating from the multiple paths the wave can follow between the source transmitter and the direction-finder. This is accentuated by the fact that, at HF, direction-finders often are remote from the area of interest. Consequently, the DF measurements are often made with a low *S*/*N* ratio and, therefore, the measurements can be relatively unstable.

Other features of the range below 30 MHz make calculation of the location difficult:

– spectrum congestion (frequent interference);

– geographical areas and non-visibility periods for some frequency ranges.

A single bearing is not sufficient to allow satisfactory location calculation. To perform a good bearing at HF, several individual bearings are necessary to obtain a significant mean bearing.

But it must be remembered that the complex paths followed by waves through the ionosphere may not correspond to great circles on the earth surface, which brings a bias at the azimuth-measurement level and, therefore, at the location-calculation level.

Above 30 MHz

In the VHF and UHF ranges wave propagation is primarily line-of-sight, via diffraction or scattering. Consequently, direction-finders should be installed in the vicinity of the area to be monitored, typically urban areas. Although the signal-to-noise ratio may be poor, the signal is usually received from a constant and stable direction. Such conditions permit acquiring reliable bearings in a relatively quick and easy way.

However, the measurement can be difficult due to the presence of interference and because of the reflections experienced by waves. This is especially the case in urban areas and when mobile DF stations are used.

Usually, simple measurements may be made in 10 ms or less, but it is desirable to integrate the results over an appropriate period consistent with the signal duration and receiving conditions. This is especially important when using mobile DF stations.

Reliable bearings that minimise the effects of reflections should only be taken while the DF unit is moving, unless it is situated at a spot clear of any obstructions.

Modern direction-finders may perform, in addition to conventional bearings, a number of technical measurements such as centre frequency, modulation rate, and bandwidth.

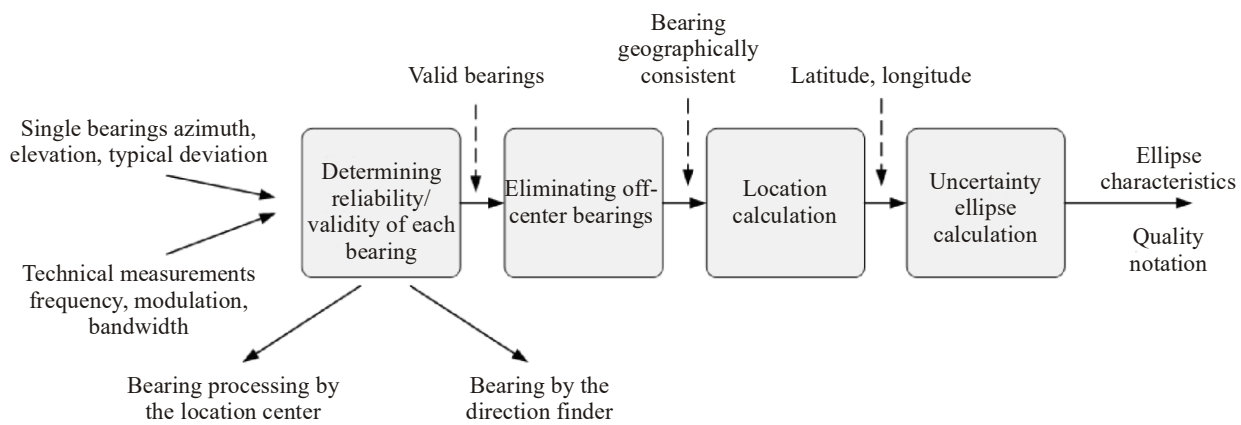
As such measurements may be made under favourable conditions (good signal-to-noise ratio), they can be reliable and permit efficiently performing the bearing data reduction.

5.7.3.1.3 Location calculation steps

Figure 5-55 shows a chart of location calculation.

FIGURE 5-55

Chart of location calculation



Spectrum-4.7-09

Determining reliable bearings

Sorting out the individual DF bearings can be performed at the monitoring/DF stations or at the location centre. Choosing between the two approaches is directly related to the capabilities of the links used between monitoring/DF stations and the location centre for routing the remote controls.

a) Fast links

If links have such a rate that exchanges between calculation monitoring/DF stations are fast (for example, a high-speed Wide Area Network), it may be useful to route to the location centre the bearings of each station in real time. A station bearing is then analysed with respect to bearings obtained by the other station at the same time. Rejecting a doubtful bearing is performed not only with respect to the bearings obtained by the same direction-finder but with respect to the bearings obtained in a synchronous manner by the other stations. At the end of alert, the location centre is provided, for each direction-finder, with a number of individual bearings. These bearings are statistically processed (bar chart, single linkage, etc.), to determine the bearing(s) characteristic of each direction-finder, as well as the corresponding typical deviations.

The advantage of such a type of system is to use simple processing at the direction-finders. This type of operation allows real-time display of the behaviour of direction-finders. At the location centre it is possible to manually select particular measured lines of bearing on the tracked transmission.

b) Slow links

If links have such a rate that each exchange between location centre and DF stations is time costly, that is, when the communication time is greater than the measurement time, making reliable bearings should be performed at the DF station. Making a reliable result is achieved by averaging the individual bearings regarding the signal of interest for the location centre. So, know-how is required at the direction-finder for classifying the individual bearings. Classifying can be performed from several information items:

– azimuth separation

– consistency of the measured centre frequency

– consistency of elevation angle between the various bearings

– likelihood of elevation angle in regard to propagation characteristics

– technical-analysis parameters enabling identification of the desired signal.

The advantage of this type of system is to make it possible to use low-rate links (e.g. conventional telephone links). On the other hand, this type of system needs direction-finders able to analyse their own bearings and to separate the data in case of receiving multiple transmissions. This type of system is well suited for location in the VHF/UHF range where DF bearings are relatively stable in time.

Eliminating non-convergent bearings

This step is manually performed in some location systems. An automatic method permitting geometrically determining the non-converging bearings is proposed here (see Fig. 5-56).

This method consists in examining for each instance the number of shootings consistent with that instance. On each shooting, the area covered by the own angular error of each of the shootings is constructed.

When areas partly overlap, it is said that shootings can be associated. So, for each shooting, the various associations possible are examined. The association including the largest number of shootings is kept. If the largest number of shootings is attained by several associations, then the association obtained with the best bearings and the best aperture angle in regard to the target is kept. Shootings that are not parts of the best association are declared off-centre and are not kept for calculating the location point.

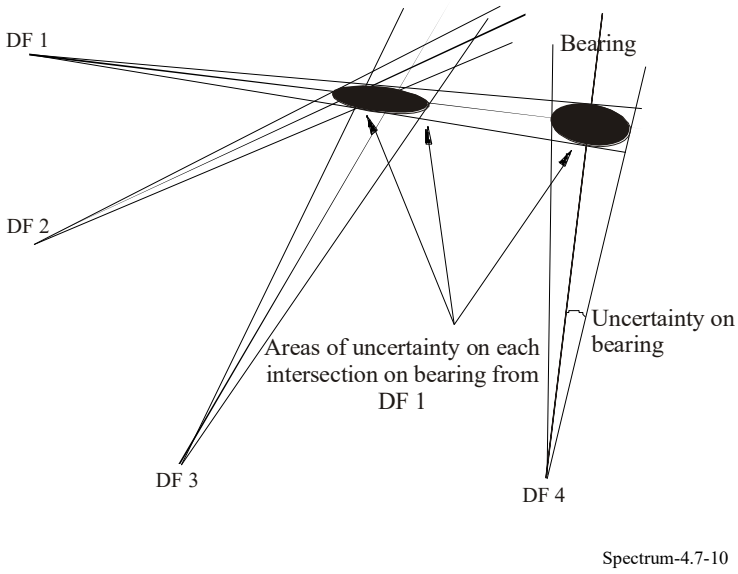
This method offers the advantage of being constructed on the angular errors, valid at short- or long-range.

Evaluating the location point

In this step, a number of bearings consistent with one another is provided, but which do not all cross the same geographical point. The purpose of this step is to determine the optimum position of the location point.

FIGURE 5-56

Validation / elimination of bearings unrelated to expected source (DF 1, DF 2, DF 3 can be associated, DF 4 cannot be associated)



The optimum point is searched applying the least error squares method. The point minimising the angular variations to be applied to each bearing is searched in order to aim at this point.

If P is any one point and d_1, d_2, d_3,... the angular variations to be applied to each bearing to intersect P and v_1, v_2, v_3,... the variances of the various bearings.

Given S_p the following quantity:

$$S_p = (d_1^2/v_1) + (d_2^2/v_2) + (d_3^2/v_3) + \cdots \tag{5-47}$$

The optimum point is the point minimizing S_p.

Several approaches exist to solve this problem:

– triangulations;

– methods of large circles, spherical triangles (long distances).

For more approaches, see [Stansfield, 1947], [Barfield, 1947].

Implementing such methods on computers raises no problem. But it must be remembered that all methods calculate an estimate. No mathematical formula exists giving the exact position.

Visually estimating the optimum point is a difficult exercise even with few bearings. When using two direction-finders, the intersection of two bearings gives one point, but because of the errors, it is not possible to assert that this point is the transmitter location. When using three direction-finders, a triangle is obtained but, due to errors on each bearing, it cannot be ensured that the transmitter is located within the triangle.

Calculation of the uncertainty ellipse

The uncertainty ellipse is the area centred around the optimum point.

The calculation of the uncertainty ellipse relies on [Stansfield, 1947]. This calculation is performed from typical deviations of the various bearings. For this typical deviation to be significant, the system must possess enough individual bearings to be capable of calculating a significant typical deviation value.

The present trend for direction-finders is to provide a quality notation incorporating the conditions under which the DF bearing was performed, rather than a real typical deviation. In such a context, the uncertainty ellipse calculation will only be an approximation. The trend of location system is to determine a quality notation for location.

The quality notation for a location represents:

– The agreement of direction-finders with one another on designating the same point.

– The persistence of direction-finders in always designating the same point.

The agreement is strong when several direction-finders designate the same point.

The persistence is strong when a variation in the bearings of a direction-finder has little influence on the optimum point calculated using all of the bearings (inertia).

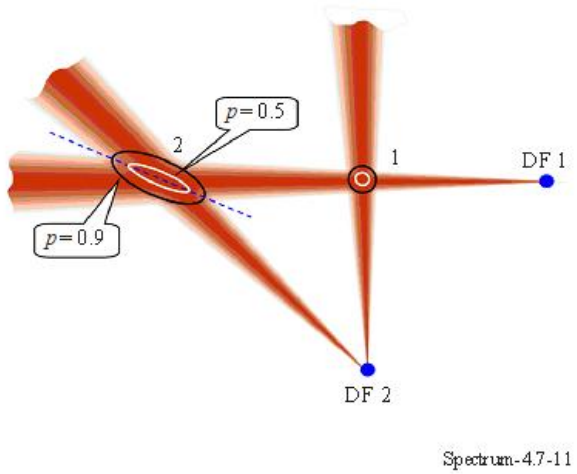
5.7.3.1.4 Distribution of location uncertainty values

Even where there are no extraneous influences on bearings (such as reflections from local features, buildings, metallic structures and so on, as well as the effects of the radio propagation medium) and the bearing lines from all the direction finders used in the triangulation process intersect at a single point, the sought transmitter may be located not at that point but within the bounds of an uncertainty ellipse determined by the instrument (or system) location uncertainty (error) of each direction finder (see § 5.7.2.1.1). This can be seen in Fig. 5-57, where the angular bearing line distributions from the two direction finders, DF 1 and DF 2, within the bounds of the specified instrument uncertainty of the direction finders are conventionally portrayed in the form of segments with fuzzy edges. The angular distribution of the bearing lines within such segments may be assumed to be Gaussian where the bearing uncertainty values are from 1°-2° r.m.s.

From the two cases in Fig. 5-57 in which the bearing line distribution segments from direction finders DF 1 and DF 2 intersect, it follows that where the two segments intersect at 90° (situation 1) the location uncertainty is at its lowest. In this case, where the bearing uncertainties of the direction finders used in the triangulation process are equal and the distances from the direction finders to the region in which the segments intersect are the same, the uncertainty ellipse becomes circular.

FIGURE 5-57

Two cases of intersection of bearing line distribution segments from the two direction finders DF 1 and DF 2



As the angle of intersection between the segments decreases (situation 2), the major axis of the ellipse, which is normally taken as a measure of the location uncertainty, rapidly lengthens, extending to infinity as the angle reaches 0°. The same occurs where the angle increases to 180°. In the case of angles approaching 0° and 180°, location using only two direction finders therefore becomes impossible, making it necessary to bring in a third direction finder located away from the line linking the first two.

From the intersection of the segments in the case of small angles it can clearly be seen how the change in the length of the major axis of the location uncertainty ellipse relates to the probability ***p*** of locating the sought transmitter within it. As probability ***p*** increases, the axes of the ellipse (major and minor) also increase, resulting in a corresponding increase in the location uncertainty determined by the length of the major axis of the ellipse.

From Fig. 5-57 it can be seen that the length of the major axis of the uncertainty ellipse depends on a variety of factors, such as:

– the bearing uncertainties inherent in the direction finders used in the triangulation process;

– the distances between the area in which the bearing line distribution segments intersect and the respective direction finders;

– the angle at which the bearing line distribution segments intersect.

It follows from this that the location uncertainty, determined by the length of the major axis of the ellipse, will take different values at different points within the overall location coverage area.

The characteristics of uncertainty ellipses which determine the location uncertainty at each point of the overall location coverage area may be calculated from the two-dimensional probability density of the Gaussian distribution curve, the determination of whose parameters becomes considerably more complex as the number of direction finders involved in the triangulation process increases, particularly where those direction finders have differing bearing uncertainty values. The bases of the mathematical tool for performing such calculations are presented in [Kogan and Pavliouk, 2004a], and the software used to implement the methodology is described in [Krutova *et al*., 2005] and [ITU Handbook, 2005].

The calculation results give the distribution of the location uncertainty values throughout the overall location coverage area. This distribution may be represented graphically in the form of adjacent subareas whose boundaries correspond to the established location uncertainty values, as shown in Fig. 5-58.

The location uncertainty gradations are shown according to the palette located in the upper right corner of Fig. 5-58. The totality of these subareas within the bounds of the overall location coverage area is referred to as the "location coverage template (LCT)" [Kogan and Pavliouk, 2004a], [Kogan and Pavliouk, 2004b], [ITU Handbook, 2005] and [Krutova *et al*., 2006].

FIGURE 5-58

Location coverage template with three direction finders, DF1-DF3

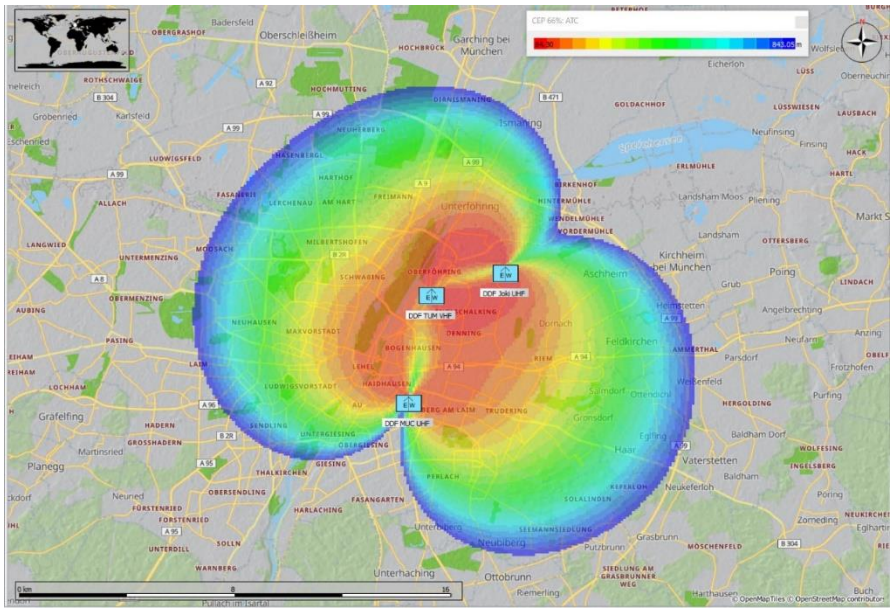


Figure 5-58 shows that for a given arrangement of direction finders within the territory in question, the lowest location uncertainty values lie at approx. 84 m (subarea shown in dark red). These values occur where the bearing lines from the direction finders intersect at angles close to 90°. The highest location uncertainty values in this example lie at approx. 840 m (subarea shown in dark blue). This occurs at the edges of the overall location coverage area, i.e. at the greatest distances from the direction finders. In the narrow strips where the bearing lines from the direction finders meet at angles close to 0°, the location uncertainty lies at approx. 400 m (subareas shown in green). The example shows the considerable value spread (a factor of 10) that is found in

the location uncertainty values depending on the above-mentioned factors. This needs to be taken into account in the planning of direction-finder networks.

A detailed analysis of the characteristics of location coverage templates is given in [Kogan and Pavliouk, 2004b] and [Nurmatov and Titov, 2005], while their use in the planning of spectrum monitoring networks is described in § 7.8 and Report ITU-R SM.2356.

Insofar as the calculation of location coverage templates takes account only of the instrument (system) errors inherent in the direction finders, the location uncertainty values reflected in such templates are the minimum possible and attainable under certain idealised conditions. Nevertheless, this information is of considerable value when it comes to the planning and optimisation of spectrum monitoring networks (see § 7.8 and Report ITU-R SM.2356).

5.7.3.1.5 Map display

The bearing lines and their cross-point are also indicated on a map display, which allow the operator to easily find the estimated position of the emission. In the case where the emission is made from a mobile unit, the operator can estimate the moving direction of the mobile unit by watching the cross-point on the display.

For more information about mapping, see § 7.2.

5.7.3.2 Time difference of arrival method (TDOA)

5.7.3.2.1 General principles

The Time-difference-of-arrival (TDOA) method determines an emitter location by using the relative arrival times of a signal at multiple receive locations. TDOA systems offer flexibility in antenna selection and placement, as TDOA accuracy is minimally affected by nearby reflectors. This flexibility allows for consideration of other critical factors, such as antenna size and weight, station complexity, ruggedness and frequency coverage. The widespread availability of SDR-based wideband RF receivers with built-in GNSS-based time stamping makes TDOA systems a cost-effective solution to many localisation applications. Furthermore, the ability to utilise any type of antenna (compact, directional, wideband or selective ones) allows for versatility to suit different applications.

This adaptability, especially the option for compact antennas, also enables fast and easy deployment compared to the efforts required to mount direction-finding systems. For this, TDOA installations are attractive for both fixed and temporary installations.

The ability to use selective and / or directional antennas allows to focus on the frequency range and spatial region of interest.

It is often stated that TDOA is less accurate for narrow-bandwidth signals than it is for wide-bandwidth signals. While generally true, this statement only considers signal bandwidth. Wider bandwidth signals have shorter-duration temporal features that can improve TDOA accuracy, especially under high multipath conditions. However, location accuracy is also affected by received signal-to-noise ratios, which is generally better for narrow-band signals at lower-frequencies. Nonetheless, as an inherent principle, TDOA is based on correlating the received waveforms, and as such the signals act as a quasi-matched filter – making the best of the available SNR, which is more than an energy-based detector can do.

It is important to understand that TDOA methods are suitable for most modulated signals, but cannot be used to locate an unmodulated, continuous carrier: the signals have to exhibit a feature that can be used as a unique time reference, such as the change of a transmitted bit. The clearer that feature is in the signal, the better the TDOA works. This makes it easier for the system to tackle with digitally modulated signals, but also analogue communication sources can be located.

The main idea for TDOA is as follows: an electromagnetic wave needs time to travel from its source to the location of a receiver. In most cases, this time cannot be measured by direct means. By comparing the times of arrival at different, well-known receive locations, the distances from the source to these locations can be determined. It takes at least three of these locations to derive the source's location unambiguously by intersecting the contour-lines formed by those distances. This applies to a 2D-localization. For localization results in three dimensions, a minimum of four sites, along with the altitude of each receiving antenna is required.

In free space, electromagnetic waves propagate at speed of light, c. This means that one nanosecond of travel time corresponds to 30 centimetres of distance travelled. This makes it obvious that TDOA systems call for a very good time synchronization method.

For a given difference of arrival time $\Delta t = t_2 - t_1$ of a signal received at two different locations, a corresponding difference of travelled distance ΔD can be derived, using the speed of light c and optionally the group delays $t_{g1}$and t_{g2}introduced by e.g. the antenna cables:

$$\Delta D = d_2 - d_1 = c((t_2 - t_{g2}) - (t_1 - t_{g1}))$$

This difference in travelled distance yields a hyperbola that restricts the possible locations of the emitter. Figure 5-59 illustrates this concept: the green line shows the hyperbola resulting from the time difference or arrival of the signal emitted from the red dot, as measured at the black dots. The receiver reached first by the signal (R_1 in this case) is at the focal point of the hyperbola. To determine the source of the emission without ambiguity, a third receiver is required.

If the two receivers lie at (R,0) and ($-R$, 0), the equation of the hyperbola is given by:

$$\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1$$

with

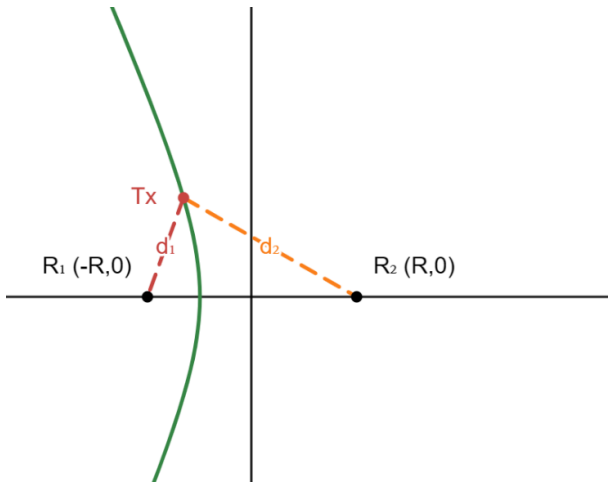
$$a^2 = c^2 \frac{\Delta t^2}{4} \text{ and } b^2 = \frac{R^2}{4} - a^2$$

where $2R$ is the distance separating the two receivers.

The time difference is obtained by comparing the absolute detection times of a signal event at the receivers (TOA method), or by finding a peak in the cross-correlations of the pairs of signals (TDOA method). These two methods are discussed in § 5.7.3.2.2 on TDOA implementations.

FIGURE 5-59

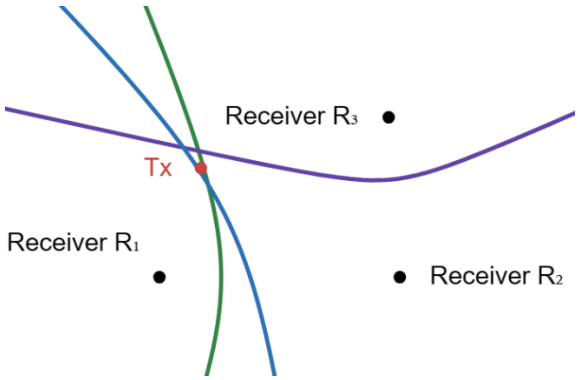
Time-difference based on distance difference $\Delta D = d_1 - d_2$



Ignoring special-case geometries, TDOA systems require a minimum of three receivers to locate a source in two dimensions. As illustrated in Fig. 5-60, with three receivers there are three possible pairings of receivers producing three different time-difference observations, and correspondingly, three different hyperbolic lines, which intersect at a common point under ideal conditions. The signal source is located at the intersection of the hyperbolic lines. While three receivers are required, only two pairings of receivers are required for geolocation. In theory, the third receiver pairing is redundant. However, in non-ideal environments the quality of the time-difference data will vary with receiver pairings. For example, in Fig. 5-60 the signal source is physically closest to receiver R_1. Assuming higher signal strength at R_1, the R_1–R_3 (green)and R_1–R_2 (blue) pairings may both produce better time-difference estimates than the R2-R3 pairing (violet). Advanced location algorithms often take advantage of this redundancy to improve location accuracy.

FIGURE 5-60

Signal source is at the target triangle



5.7.3.2.2 TDOA Implementations

There are two fundamental methods for computing the time-difference-of-arrival for a signal arriving at a pair of receivers. In the first method, each receiver determines and reports a signal's time-of-arrival (TOA) to the TDOA host computer. The host computer then subtracts one receiver's TOA estimate from another to compute the time-difference. In the second method the receivers digitize the signal and send the time-stamped samples to the host computer where any number of numerical methods may be used to estimate the location. The following paragraphs give details on those methods.

TOA method

Establishing a signal's time-of-arrival at the receiver is attractive in situations where data communications bandwidths are restricted. With this method, only the time at which a signal arrives needs to be communicated. The drawback to this method is that, unless the signal has known characteristics which enable the receiver to accurately determine time-of-arrival under poor channel conditions, this method requires: high signal-to-noise ratios (SNR's), high signal-to-interference ratios, and limited multipath distortion at all receivers. This method is particularly well suited to intermittent or burst signals whose edges can be precisely measured in time by the receivers. Many digital communication protocols rely on such signals, such as the maritime Automatic identification system (AIS) or the aeronautical ADS-B, ACARS and VDL-M2 protocols.

The accuracy of the TOA method can be enhanced using known information from digitally modulated signals. The data-aided method applies to systems that have standardized parameters ("discriminant signals") in service channels or in traffic channels that are transmitted continuously or at regular intervals, such as training sequences or pilot carriers. By exploiting the discriminant signal characteristics in the TDOA calculations, it is possible to:

– benefit from a significant gain in signal detection, which improves the sensitivity and the reliability;

– separate the sources in the same band when they use different discriminant signals for synchronisation;

– associate an estimated location with a specific emitter by utilizing decoded digital signal data containing an identifier (e.g. a ship or aircraft registration number, or a radio ID).

TDOA method

TDOA receivers synchronously digitize the signal and then transfer the time-stamped I/Q-samples to the TDOA host computer. The drawback to this method is that hundreds, potentially even thousands of samples from every receiver need to be communicated to the host computer for every update of a signal's estimated position. Slow data networks will limit the rate at which location estimates are updated. For this reason, TDOA systems typically implement some kind of adaptive data flow control to prevent slow data links from affecting the performance of the TDOA host computer. The primary advantage of this method is that it supports the use of algorithms which work on most signals, under poor channel conditions, without requiring significant knowledge of the signal's characteristics. It provides more information, such as time, spectrum, and correlation plots. Note that a priori knowledge about the characteristics of the signal may be necessary to acquire certain

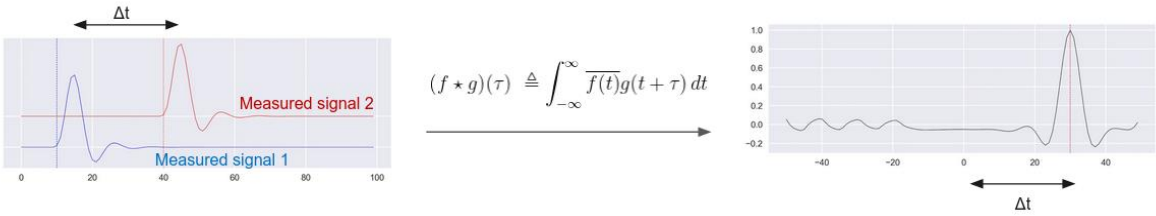
signals (e.g. squelch level and transmission length for burst signals). For many spectrum monitoring applications, the TDOA method is preferred due to its cost, ease of deployment, localisation performance and flexibility. This method can also reduce the computational resources needed in the receiving station, provided the data transmission and adaptive flow control aren't overly complex.

Computing Location in TDOA systems

A common approach for computing location in TDOA systems is to first determine the time-difference-of-arrival for each receiver pairing by computing the cross-correlations of the associated timestamped I/Q data as illustrated in Fig. 5-61.

FIGURE 5-61

Cross-correlation of two measured signals and TDOA result

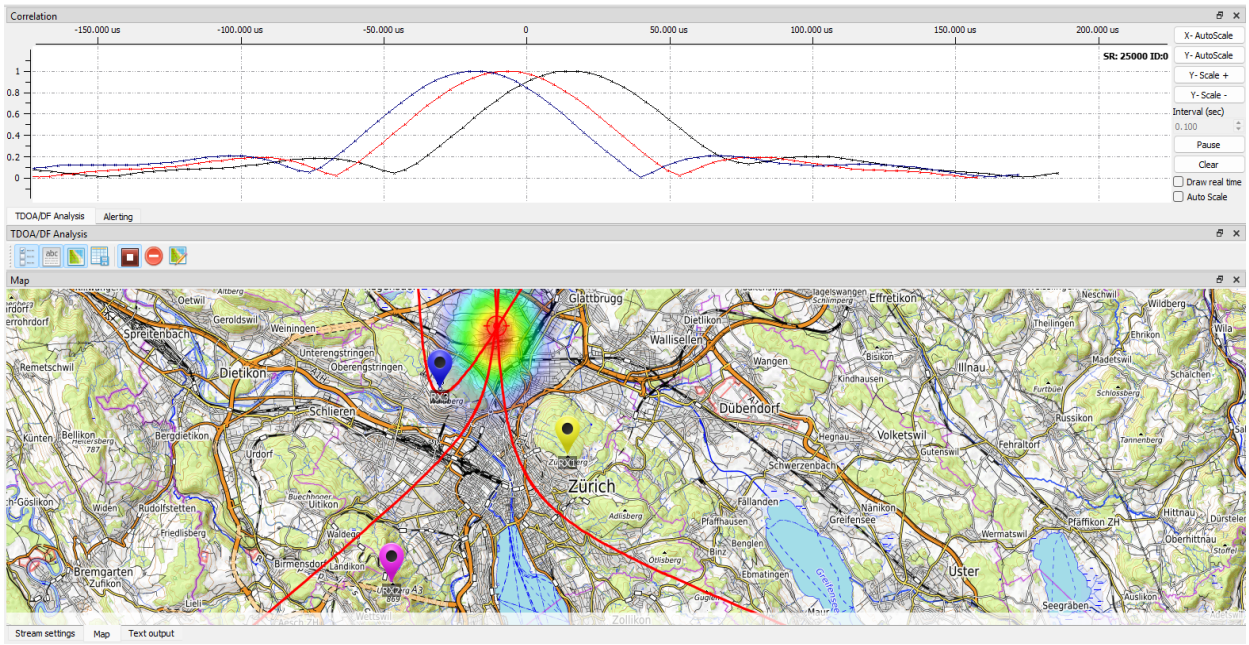


Algorithms then estimate the point-of-intersection of the hyperbolic lines corresponding to the time-difference values. This is analogous to the lines-of-bearings (LoB's) approach used in direction-finding systems. In DF systems, angular errors will often prevent three or more LoB's from converging on a single location. In TDOA systems, timing estimation errors have a similar effect on the hyperbolic lines as illustrated in Fig. 5-62.

The results of these computations are often presented in the form of likelihood maps, where colour or intensity is used to indicate probable signal locations as shown in Fig. 5-62. When available, spectrum, time, and correlation plots can aid in the interpretation of TDOA results.

FIGURE 5-62

TDOA measurement result of a TETRA downlink signal



Other, usually proprietary computational techniques may also be used to estimate location. These techniques are generally more sophisticated at dealing with multipath, multiple co-channel signals, and other TDOA

complexities. These techniques may also incorporate amplitude information, and in the case of antenna arrays, angle-of-arrival information.

5.7.3.2.3 Factors affecting accuracy

Recommendation ITU-R SM.2139 discusses localisation quality and summarizes procedures for measuring the localisation quality of TDOA systems. Before discussing the factors that affect it, the relevant metrics for quality are defined:

The quality of a TDOA solution is typically described by its accuracy and precision.

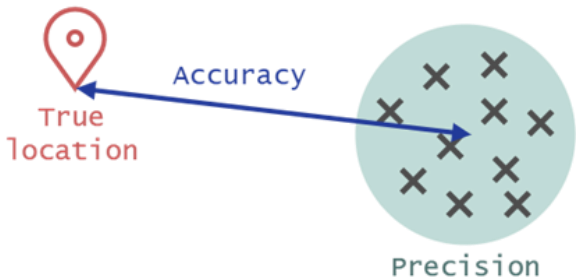
Accuracy refers to the distance between the mean of all computed locations $\overrightarrow{p_i}$ and the true location $\overrightarrow{p_t}$ of the signal source. It is the mean location error for a set of N measurements:

$$\text{Accuracy} = \frac{1}{N}\sum_{i=1}^{N} e_i = \frac{1}{N}\sum_{i=1}^{N}\|\overrightarrow{p_t} - \overrightarrow{p_i}\|$$

Precision describes the spread of the estimated locations around their mean. It is most commonly defined as the standard deviation of the location errors. Low precision means that location estimates have a large spread, which requires a larger area to be searched for the source of interest. Figure 5-63 illustrates the difference between accuracy and precision.

FIGURE 5-63

Accuracy and precision



In general, there are several factors that affect the localisation accuracy and precision. These factors are discussed in the paragraphs below. In TDOA systems, the precision is mostly independent of the distance between the emitter and the receiver network whereas, in comparison, the precision associated with AOA is directly related to the distance between the emitter and the AOA system.

Geometry

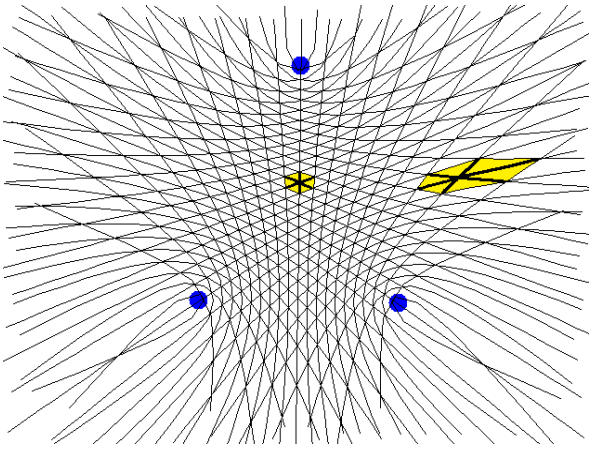
The location of the receiving stations with respect to the area of interest is also paramount since the most accurate location estimation occurs close to the centre of the convex shape described by the position of the receivers. As a consequence, an ideal TDOA system relies on receivers encircling the area of interest.

The relative positions of receivers and signal sources impact the TDOA localization accuracy.

Figure 5-64 illustrates the basic error mechanism. In this figure, hyperbolic lines are plotted for all three receiver pairings across a range of uniformly spaced time differences. Assume the lines in this example are spaced at 1 µs intervals, and that multipath and other errors can introduce up to 1 µs of error in the time-difference estimation.

FIGURE 5-64

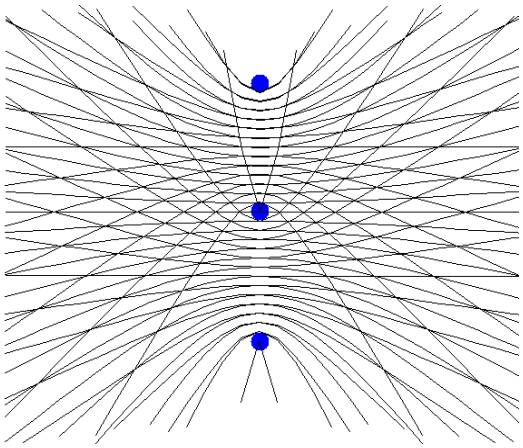
Geometry affects on TDOA accuracy



Spectrum-4.7-16

FIGURE 5-65

Poor receiver geometry



Spectrum-4.7-17

Under these conditions, the shaded areas represent the areas of uncertainty bounded by time-shifts of +/–1 µs using all three receiver pairings. From this figure it is easy to observe that the best accuracy is near the centre of this particular arrangement of receivers. Precision degrades outside of the triangular area defined by the three receivers, and is clearly poor in the areas immediately "behind" the receivers. In regions well outside of the area defined by the three receivers, the hyperbolic lines tend to run parallel, limiting TDOA systems to reporting something similar to a line-of-bearing.

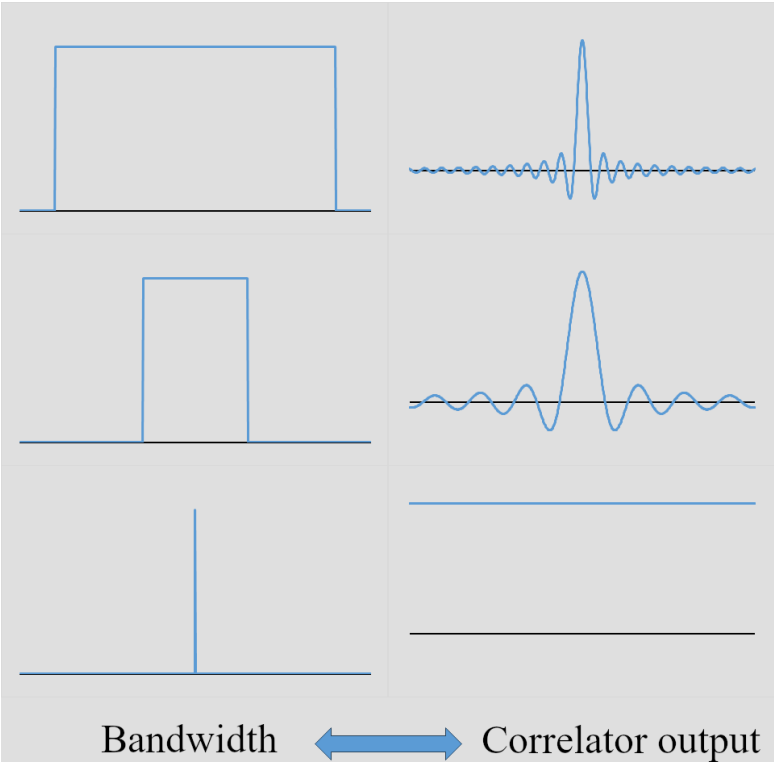
Localisation accuracy is often intentionally compromised to take advantage of existing receiver sites and other infrastructure. Figure 5-65 (above) illustrates a straight-line geometry. With this geometry horizontal precision is generally poor. Also the location system cannot distinguish between a signal source to the left of the sensor line, and one to the right that is the mirror image about a vertical line connecting the sensors.

Signal bandwidth, periodicity and multipath

Signal bandwidth is the most critical factor for precision due to the inverse relationship between the time and frequency domains. As illustrated in Fig. 5-66, a wide modulation bandwidth in the frequency domain translates to a narrow $\sin x/x$ shape at the output of the correlator. A sharp correlation peak produces a more precise TDOA hyperbola. A narrower modulation bandwidth in the frequency domain produces a wider $\sin x/x$ pulse at the correlator output. This wider correlation peak produces a TDOA hyperbola with more uncertainty. All other considerations aside, wide-bandwidth signals may be located with greater precision as it is easier to determine the timing of the signal due to, especially in the presence of noise and multipath distortion.

FIGURE 5-66

Relationship between signal bandwidth and correlation result

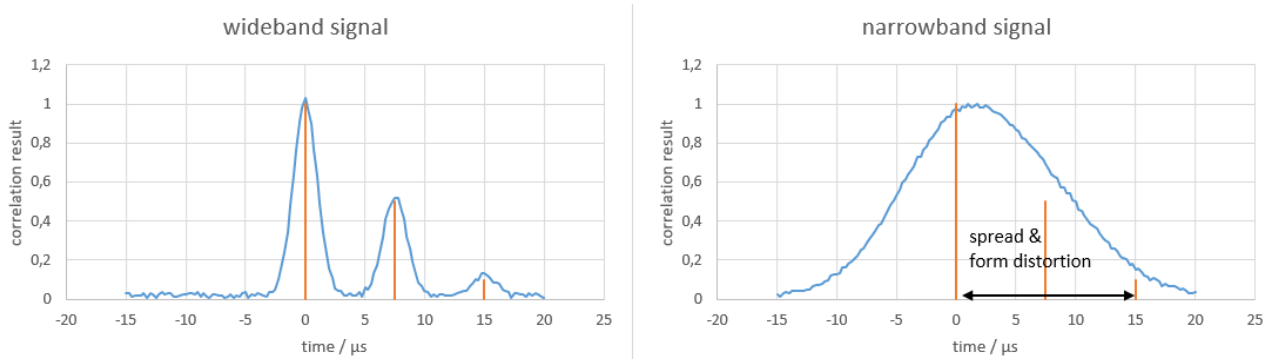


While it is generally desirable to match the TDOA receiver bandwidth to the signal bandwidth, doing so is not absolutely required, nor is it always the best approach. There are many signals that have most of their energy concentrated around a carrier allowing narrow receiver bandwidths to improve SNR, or to provide better isolation from adjacent or overlapping signals. Nonetheless, narrower acquisition bandwidths diminish the time-domain features and reduce TDOA precision.

Multipath is evident in direction-finding systems when multiple copies of a signal arrive from multiple bearings. In TDOA systems, multipath is evident when multiple copies of a signal arrive with different delays. Multipath is potentially more of an issue for narrow bandwidth signals when the signal's temporal characteristics are wide relative to the delay spread as shown in Fig. 5-67 in which the orange lines show signal components from direct and indirect propagation paths. Under these conditions the pulse-shape distortion caused by the multipath is harder to discriminate, adding error to the time-difference estimation, and therefore impacting the localisation accuracy.

FIGURE 5-67

Multipath and signal bandwidth effects on TDOA correlation



While the probability is low, it is possible for correlation-based TDOA algorithms to produce incorrect localisation results with signals that contain periodic elements. Examples of periodic elements include repeating data sequences and synchronisation pulses. False localisation may also occur in the case of signals emitted from multiple transmitters using common synchronisation signals. In this situation the system may be unable to distinguish between the cross-correlation peak of a common signal arriving at two different TDOA receivers, and the correlation peak due to common signal elements embedded in two different signals. This phenomenon may occur, for example, with Digital Audio Broadcast (DAB) signals, where performing TDOA can yield multiple correlation peaks (as shown in Fig. 5-67 on the left). When multiple peaks can be resolved in the cross-correlations, a TDOA system shouldn't assume the highest peak corresponds to the unique direct path. Instead, it should compute positions for all combinations of time differences resulting from the various peaks to ensure no possible emitter locations are missed. Displaying all these positions on a map (e.g. in a heatmap) will reveal not only the real transmitter locations but also erroneous "ghost positions". A way to minimize this problem is to have the receiver spacing smaller than the spacing of the transmitters.

Timing accuracy

Timing accuracy is fundamental to location accuracy in TDOA systems, just as angular accuracy is fundamental in direction finding systems. While good timing accuracy is necessary, it is not sufficient to ensure accurate locations. Common accuracy approximations of "a foot/ns" or "30 cm/ns" give a sense of what is possible for a given timing accuracy specification, but should not be relied on as accurate predictors of TDOA system performance. These approximations do not take into account the relative locations of the receivers, or the signal source characteristics as described above. Nor do they account for the relative timing errors between receivers, or delay errors introduced by antenna cables and filters (which might be addressed by compensation tables).

While it is possible to mix different types of receivers in a TDOA system, one should ensure all of them perform time-stamping consistently, particularly across all combinations of centre frequency and gain. The timestamp provided should ideally match the time the signal reaches the antenna connector. If time-stamping consistency is not achieved, the results will be biased, requiring proper calibration of the receivers and subsequent compensation for these biases within the TDOA host computer.

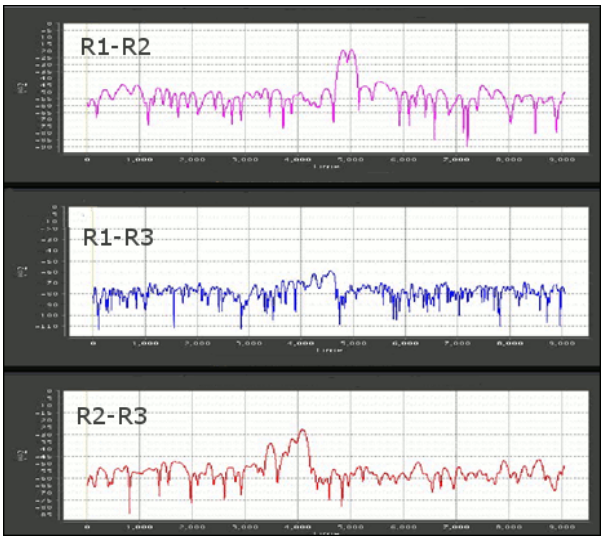
Effects of signal level, duration and velocity in correlation based TDOA

One method for determining the TDOA involves computing the cross-correlation between signals from two receivers. The cross-correlation function indicates the commonality of two signals as a function of time offset. For a signal observed over the same time interval at two different receivers, the position of the amplitude peak in the cross-correlation function indicates the delay-difference for that pair of receivers.

Figure 5-68 contains the cross-correlation plots from a single measurement in a three-receiver system. Ideally, each plot would contain a single pulse, the position of which is shifted left or right depending on the time-difference. As this data comes from an actual measurement, it exhibits the effects of real-world impairments. All three cross-correlation plots exhibit multiple pulses indicating multipath. In addition to multipath distortion, the second cross-correlation R1-R3 also exhibits the symptoms of low SNR. While the cross-correlations in this example are far from ideal, it is possible for sophisticated TDOA algorithms to extract location information from data of this quality.

FIGURE 5-68

Cross-correlations distorted by noise and multipath



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The magnitude of the cross-correlation peak is a function of the received signal power at both receivers. The cross-correlation noise level is a function of the noise level at both receivers; the degree to which the noise from each receiver is correlated, and the length of the interval over which the cross-correlation function is computed.

Noise reduction is one of the benefits of TDOA based systems. It allows geolocation of signals that are received with negative SNR at one or more of the system's receivers. While there is no theoretical limit to the amount of noise reduction that can be achieved, there are practical limits, such as the duration of the signal.

Relative motion between the signal source and the TDOA receivers introduces a frequency shift (Doppler). The frequency shift will be different for each receiver depending on the rate at which the signal source and receiver are moving towards, or away from each other. The magnitude of the frequency shift is also a function of the signal's frequency. Even without relative motion, a very small frequency shift can be observed between receivers due to finite timing synchronization accuracy.

Since frequency shifts degrade the cross-correlation calculations used by TDOA systems, these *relative* frequency shifts between receivers must be corrected to achieve accurate time-difference estimation. For that reason, it is also preferable to favour many correlations based on short acquisition length over few correlations based on long acquisition length.

5.7.3.2.4 System considerations

Receivers

Receivers should have adjustable IF bandwidths to: allow signals to be spectrally isolated from other signals; minimise noise power; and make the maximum use of a signal's bandwidth to improve geolocation accuracy.

To minimise network requirements, receivers that transfer sampled signals to the TDOA host computer should use the minimum sample rate necessary to represent the signal without aliasing. Timing accuracy should be independent of sample rate. In other words, a 20 kHz sample rate should not imply a 50 µs (1/20 kHz) timing accuracy.

An SDR receiver typically provides a down-sampled stream of IQ samples, along with a high precision timestamp, typically referring to the first sample. Based on the sampling rate, a precise time of each sample can be derived. Therefore, the timing precision depends only on the native sampling rate of the wideband ADC and not the one of the digitally down-converted signal.

To further minimize network and computational requirements, receivers should avoid as much as possible the transfer of sampled signals when signals are not present. A squelch-based acquisition or a duty-cycle approach can be used to adapt the data transfer to the available network bandwidth.

A receiver's absolute timing accuracy should be specified at the receiver's antenna connector under most, if not all operating conditions. This will avoid the introduction of timing errors by the switching of internal pre-selection filters, attenuators, or other changes to the receiver's analogue and digital signal processing elements that might otherwise affect the receiver's total group delay. As mentioned previously, this makes it possible to mix different models of receivers in a TDOA system. Even if the receiver does not account for variations in its internal group delay, errors due to the geometry of the TDOA sensor system placement will probably dominate.

Receiver timing accuracy should apply at all frequencies within a receiver's IF bandwidths. This will ensure that signals occupying a significant percentage of the IF bandwidth are not further distorted by group-delay variation. It will also ensure that a signal that is narrow relative to the IF will have good timing accuracy at any frequency offset within the IF. A receiver's final IF filter is generally the narrowest filter in the receiver and is likely to be the largest source of timing error in the receiver's internal signal path.

The TDOA system should have a facility for adding delay calibration coefficients for each receive site, especially when each installation is different in terms of RF feedline and signal conditioning. This makes it possible to compensate for delays introduced in the RF paths of the diverse monitoring stations used to capture the data.

Number of receivers

For unambiguous TDOA-based geolocation in two dimensions, a minimum of three receivers is required. While using more than three receivers can improve accuracy, this is only true if all receivers have equally good signal reception. A single receiver with poor reception will compromise several time-difference estimates, negatively impacting the results. The number of receiver pairings, and thus time-difference estimates, can be calculated as $N(N-1)/2$, where N is the number of receivers. For instance, four receivers yield six correlation pairings (double that of a three-sensor system) and six time-difference estimates. The quality of data from each pairing varies significantly based on factors like signal level and multipath. Advanced TDOA algorithms can intelligently combine or discard data from multiple pairings to enhance location accuracy. However, adding too many receivers to one measurement eventually becomes counterproductive, as the computational load increases exponentially with minimal accuracy gains.

Additional receiver and site considerations

There are several additional considerations in planning a TDOA system. Information on that is found in Chapter 2, Chapter 7 and in Reports ITU-R SM.2356 and ITU-R SM.2211.

Depending on these considerations, recommended receiver separation distance will range from hundreds of meters to tens of kilometres.

Time references

TDOA systems will typically use GNSS receivers to establish a common time reference. Users have to make certain that the reception of the time signal is stable to ensure good localization results.

Operating a TDOA system in a GNSS-denied environment makes the time synchronization of the receivers more challenging. Solutions exist to replace the need for a GNSS-based clock. For temporary deployments, one solution is to use stable oscillators (such as rubidium oscillators) synchronized in advance to provide the RF receiver with a reference (e.g. 10 MHz reference signal) and time base (PPS signal).

An alternative is to calibrate the internal clocks of the various receivers using a known emitter. By computing an estimate of the position of a known emitter using the TDOA method and tracking the resulting error, one can estimate the time offsets and clock frequency differences of the receivers.

Another alternative is to use a precision time protocol such as IEEE-1588 over the network connection. This type of installation is limited in that wired connection of all receivers is needed. But this can be useful for systems installed in buildings or campuses that have a robust wired network.

Network considerations

Network requirements are driven by:

– the TDOA method;

– the specific implementation;

– user requirements for speed and reliability.

Networking capacity and speed requirements will be greatest for TDOA systems that return sampled signals to the TDOA host computer. TDOA systems that establish TOA at the receiver will have more modest bandwidth requirements. In both types of systems, data transfers are likely to be highly asymmetrical with upload requirements exceeding download requirements at the receiver. Network bandwidth requirements will generally be greater at the TDOA host computer as data from all receivers is collected at one location.

Low latency is generally desirable in all TDOA systems. High latency may negatively impact the location update rate. It may also impact the ability to schedule TDOA measurements.

In large location systems, multiple networking technologies may be required, such as WiFi, microwave links, fibre-optic, cellular networks or satellite data links. In these systems, network connections may suffer variations in capacity and reliability due to weather, interference, delays, and loading from other network users. TDOA systems should be capable of gracefully accommodating differences in performance between the various network links, as well as outages to one or more receivers. When wireless networking is used, care should be taken to avoid interference between the TDOA receiver and the RF modem.

When public networks are used as part of the TDOA system, virtual-private-networks (VPNs) or other similar networking technology should be used to secure data transfers and prevent direct attacks on the receivers. TDOA receivers will generally have limited computational resources and may be easily overloaded by unnecessary or malicious network traffic.

5.7.3.3 AOA homing and standoff methods

Emitter localization can be performed using re-locatable direction-finders, with the advantage of using fewer DF stations. Those stations are typically mobile or portable, as depicted in §§ 3.2.2 and 3.2.3. Most mobile DF stations are mounted on a vehicle, while portable DF stations are re-locatable assets, which may require set-up and deployment before measurements can be performed. These types of units are devised to operate using two basic methods: standoff methods and homing methods.

The *standoff method* involves obtaining several discrete LoB measurements from fixed locations, which are a suitable distance from the subject emitter. The suitable distance is likely to be a function of the accuracy of the DF system, local terrain, or other conditions. Successive measurements may be made, at different locations, with as few as one portable or mobile station and combined using standard triangulation methods.

Disadvantages of the standoff method include the fact that measurement site selections are susceptible to interference from surrounding structures, and that simultaneous measurements are often impossible from multiple locations. Signal transmission times or transmitter movements may introduce location errors. The choice of the DF principle for these types of measurements should consider susceptibility to site effects, and physical arrangements for mobile and portable application.

Homing methods rely on using mobile equipment of minimal complexity and moderate accuracy. They are also effective in interference clearance operations using mobile monitoring vehicles.

This second strategy makes use of mobile equipment (usually in an automobile or aircraft), which can be rapidly moved into the vicinity of the transmitter by following successive approximations of the true line of bearings. As the distance to the transmitter is decreased, the magnitude of the absolute distance error also decreases even if the relative error in degrees remains constant. Advantages of this strategy include equipment which is lower in cost and complexity, the fact that adequate results can usually be obtained in a reasonable time, the additional fact that site error problems are much less important because the mobile unit passes lots of different locations. Finally, the DF information can be derived from sub-audible and locally-induced homing system modulation which does not disrupt the information being transmitted.

Widely available homing systems have been found to operate either in a "homing" configuration without the ability to clearly hear normal modulation components, or in an "audible" configuration when the homing circuit is switched off. This limitation is inherent with design of equipment that superimposes audible, local modulation proportional to the direction of signal arrival. Only one DF homing system is required to locate a signal source, although simultaneous use of others may speed up the transmitter's localization. Disadvantages are that inconspicuousness of stand-off capability is sacrificed, and multiple transmissions over a reasonable time period are required for adequate location of the transmitter. There are systems that can be used to locate interferences in TDD systems by using a time-gated direction-finding function. This function can be set up to focus on specific times, e.g. the time slots reserved for uplink signals. The locations of multiple different transmitters on the same frequency can be found over time.

During homing, the operators have to be aware of the direction finder's surroundings. Open spaces give the best information, while being surrounded by buildings with metal structures leads to homing into the reflected waves. If, e.g., in mountainous landscapes, the reflected waves are the dominant signal on the direction finder then these are the bearings to follow, until the direct wave get larger in magnitude than the reflected part. The more experienced the operator get with the system and procedure, the easier a homing mission will reach the transmitter of interest.

Two examples on the homing procedure to localize the source of an emission by using a mobile DF unit are shown in the Figs 5-69 to 5-75. Depending on the location, one starts by following the direction of the DF. As the reading tend to rotate away from the driven path, one can choose to circle the area or – depending on the received power levels – can just go a little back and pinpoint the most probable location. Some software tools feature sophisticated techniques to assist the monitoring personnel. Such systems exist in different levels of automation. These range from heat-map or error-ellipse based visualizations to voice-guides which direct the operators through the streets along a pattern, aimed at gathering as much data as possible in a short timeframe to close in to the location of interest. Some solutions allow to use the DF system along with a time-gated trigger. This function can be set up to focus on specific times of the emission. If DF operations are done on frequencies occupied by TDD systems, then those DF readings during the time slots reserved for uplink signals are of special interest to reach the emission's source. Two software packages dedicated to localization are demonstrated in the examples.

Figure series 5-69 to 5-71 shows and example where the software indicates the DF readings as a light blue line. While the system is on the move, the software filters all available measurements and uses statistical analysis to determine the most probable transmitter position. The result is displayed as a heat map and continuously updated.

The colours of the heat map indicate the likelihood of the transmitter's position. Received power levels along the sensor track are displayed in a colour scheme to indicate how far the transmitter is from each point on the track. On course of the figures, the vehicle moves on the main street towards the small lakes seen on the top right in Fig. 5-69, and on the middle right in Fig. 5-71. A location estimate is displayed once the heat map is sufficiently stable by a transmitter symbol (black rectangle with transmitting antenna, compared Fig. 5-71).

FIGURE 5-69

DF homing example with heatmap based software support: start of homing task

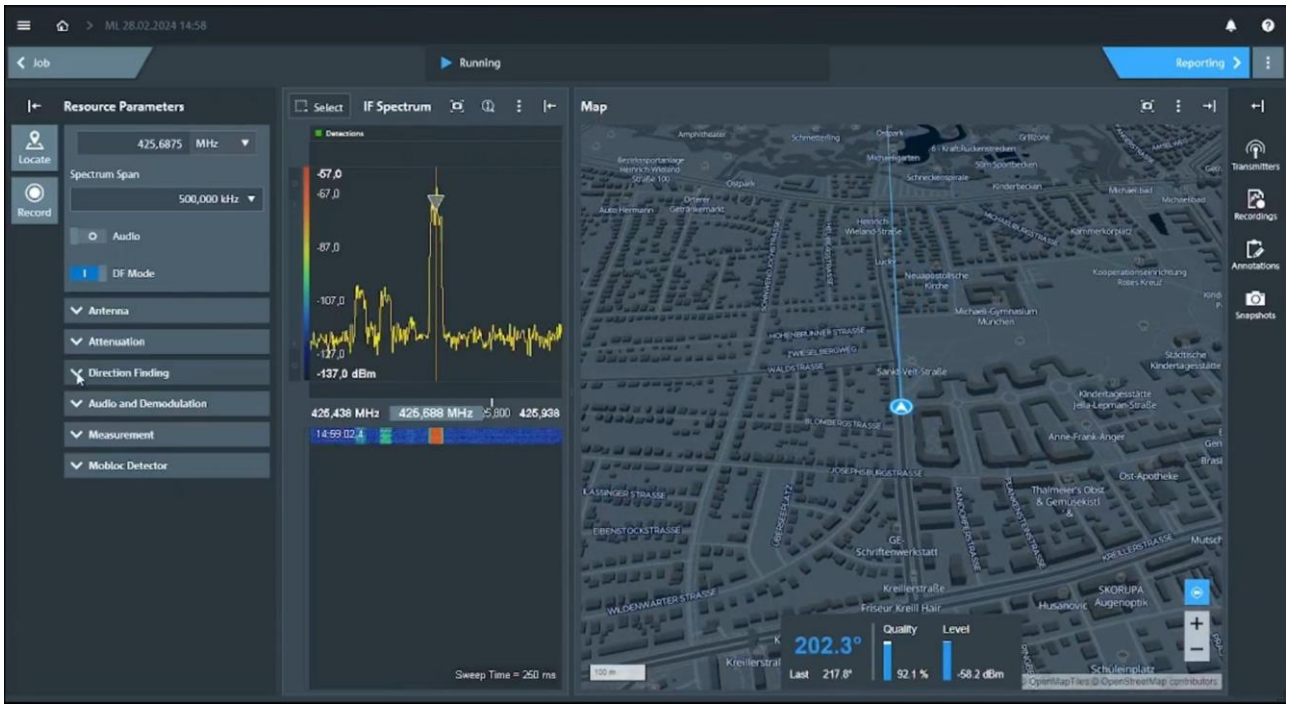


FIGURE 5-70

DF homing example with heatmap based software support: data is collected during driving, moving towards suspected location

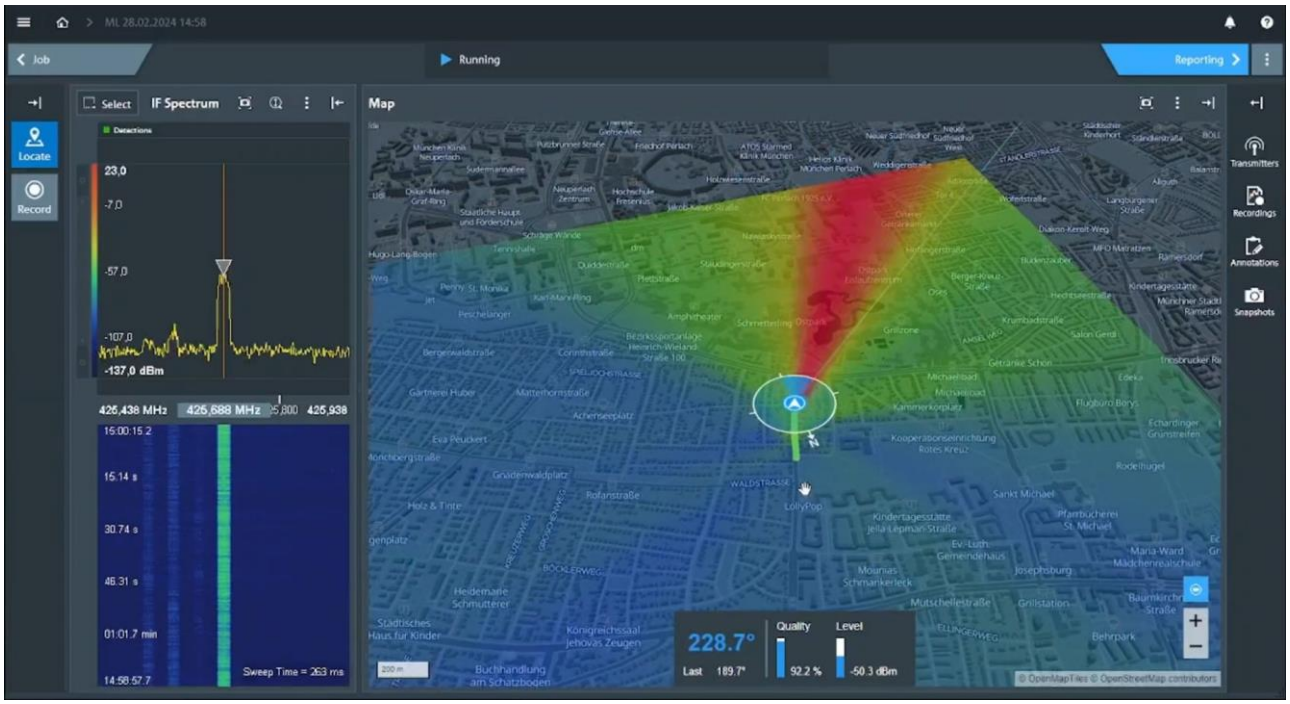
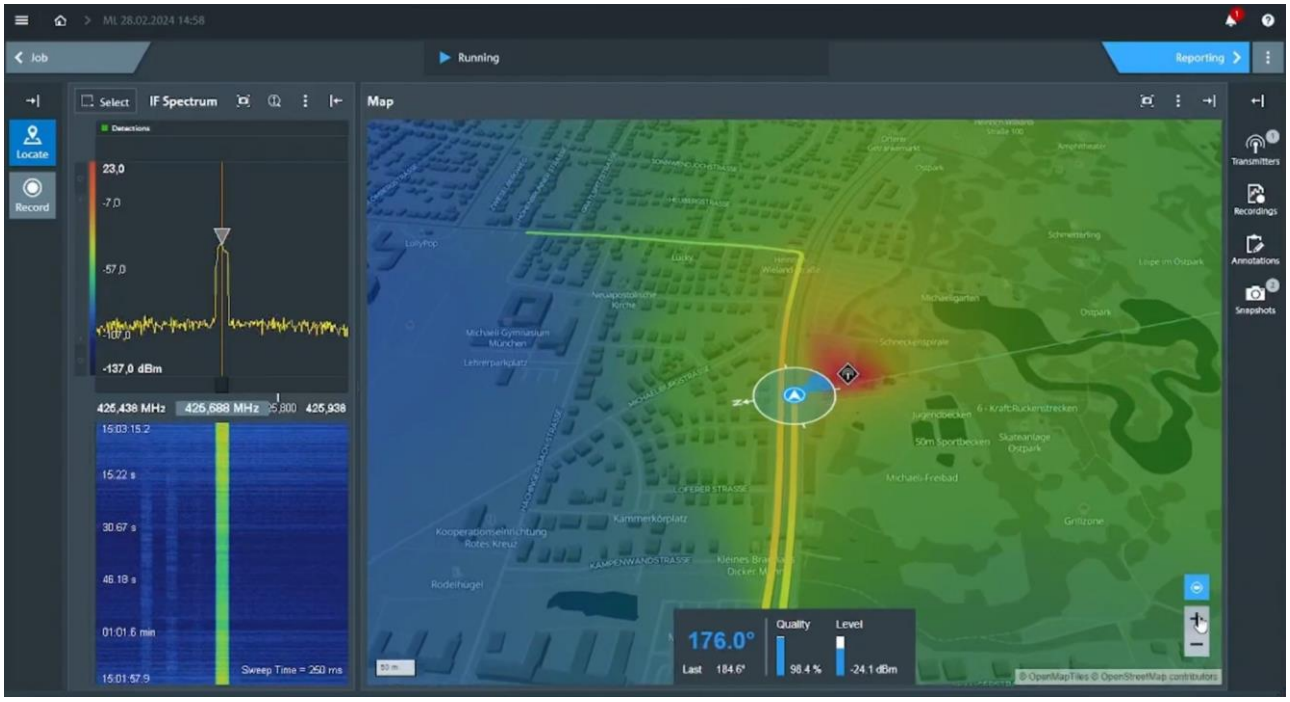


FIGURE 5-71

DF homing example with heatmap based software support: the most probable transmitter's location is found (symbol in the red area)



A different approach is to display the error ellipse of the estimated transmitter position. The error ellipse suggests that the sought location is within the ellipse The error ellipse is computed by a statistical error calculation that guesses the best estimate of emitter location based on the measured lines of bearing. The ellipse gets the smaller the more meaningful data is collected.

An example of a homing task with such a system is illustrated in Figs 5-72 to 5-75. The current DF line of bearing is shown in pink on the map, while the error ellipse is shown in purple. In the upper left of the images, the DF result is shown relative to the vehicles front to give easy driving directions such as 'left, right, forward'. The figure series illustrates how the transmitter's location estimate starts to shrink to a small spot while the vehicle passes the suspected transmitter site. After the pass, the vehicle turns to move closer towards the ellipse. The size of the ellipse decreases rapidly, comparing Figs 5-73 to 5-74.

FIGURE 5-72

DF homing example with error ellipse display: initial approach

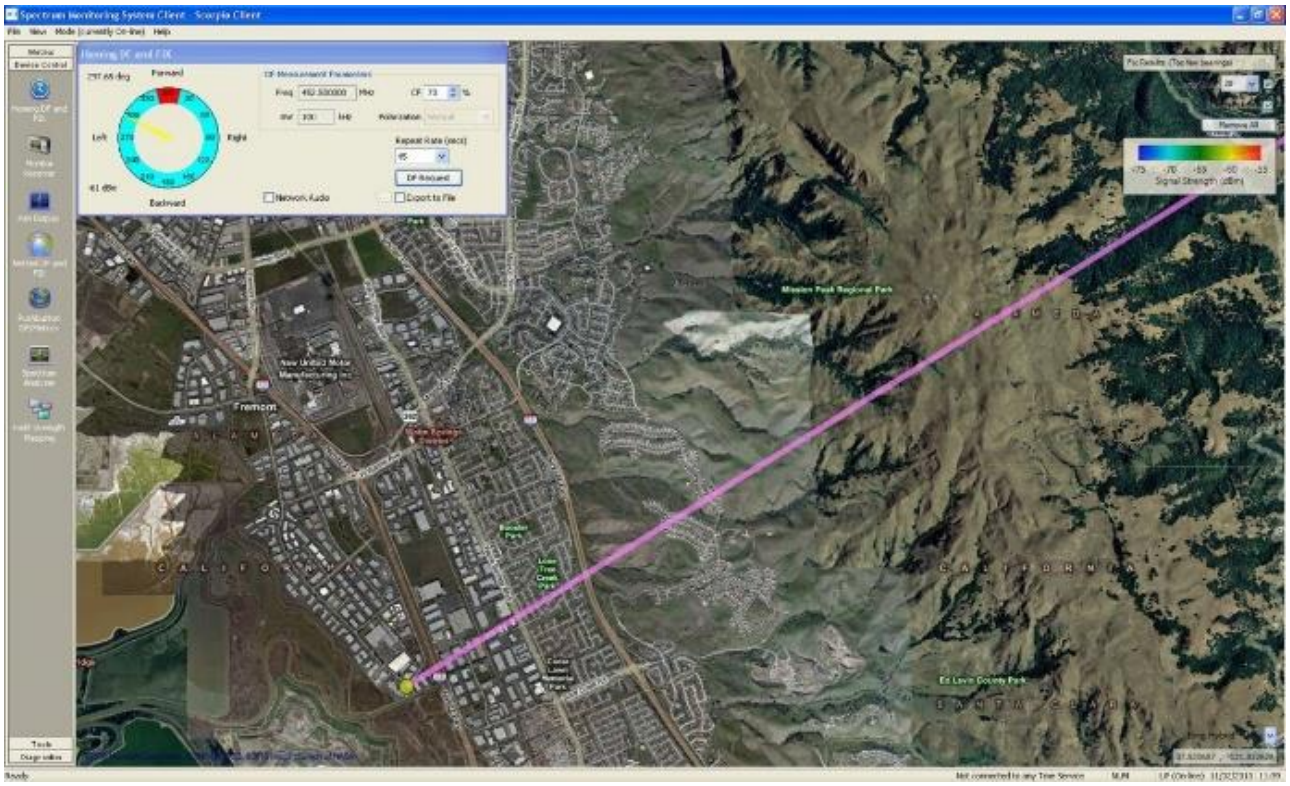


FIGURE 5-73

DF homing example with error ellipse display: target area has been passed

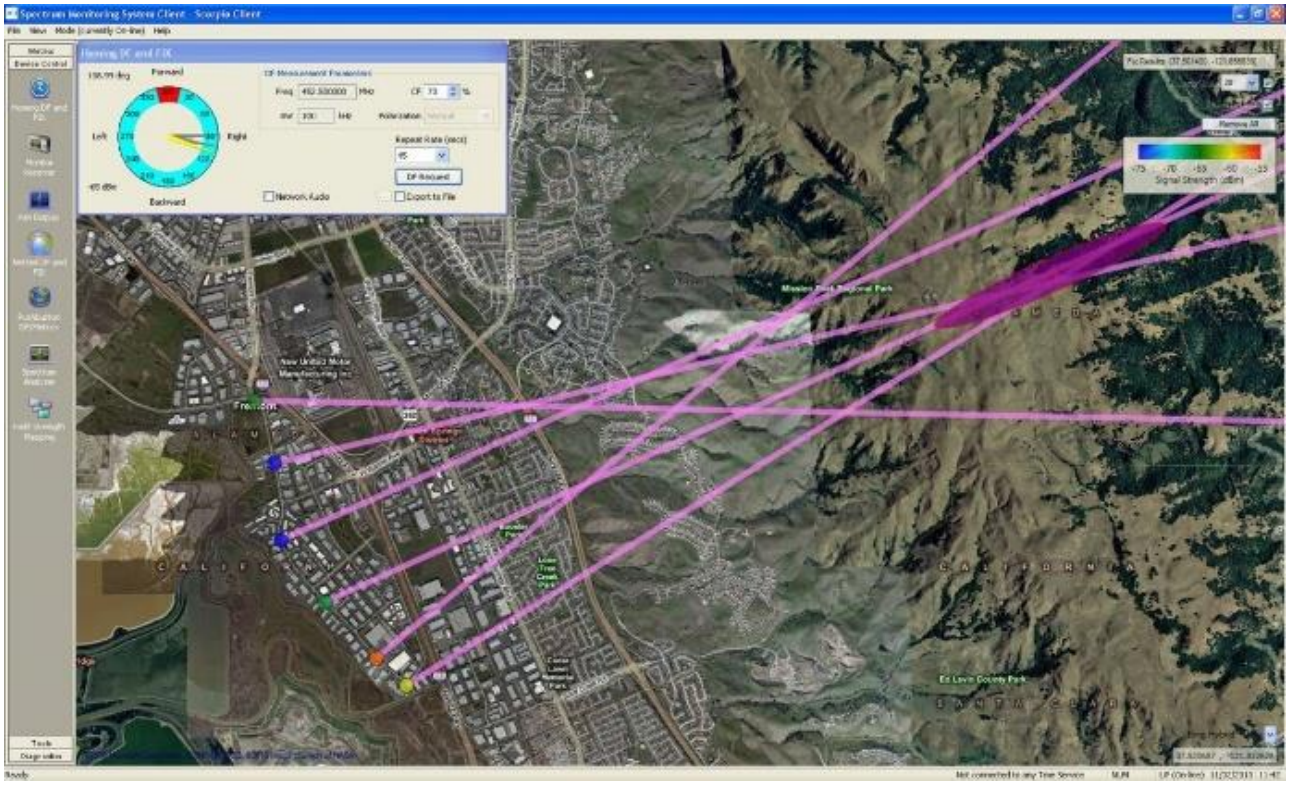


FIGURE 5-74

DF homing example with error ellipse display: change of direction towards target area

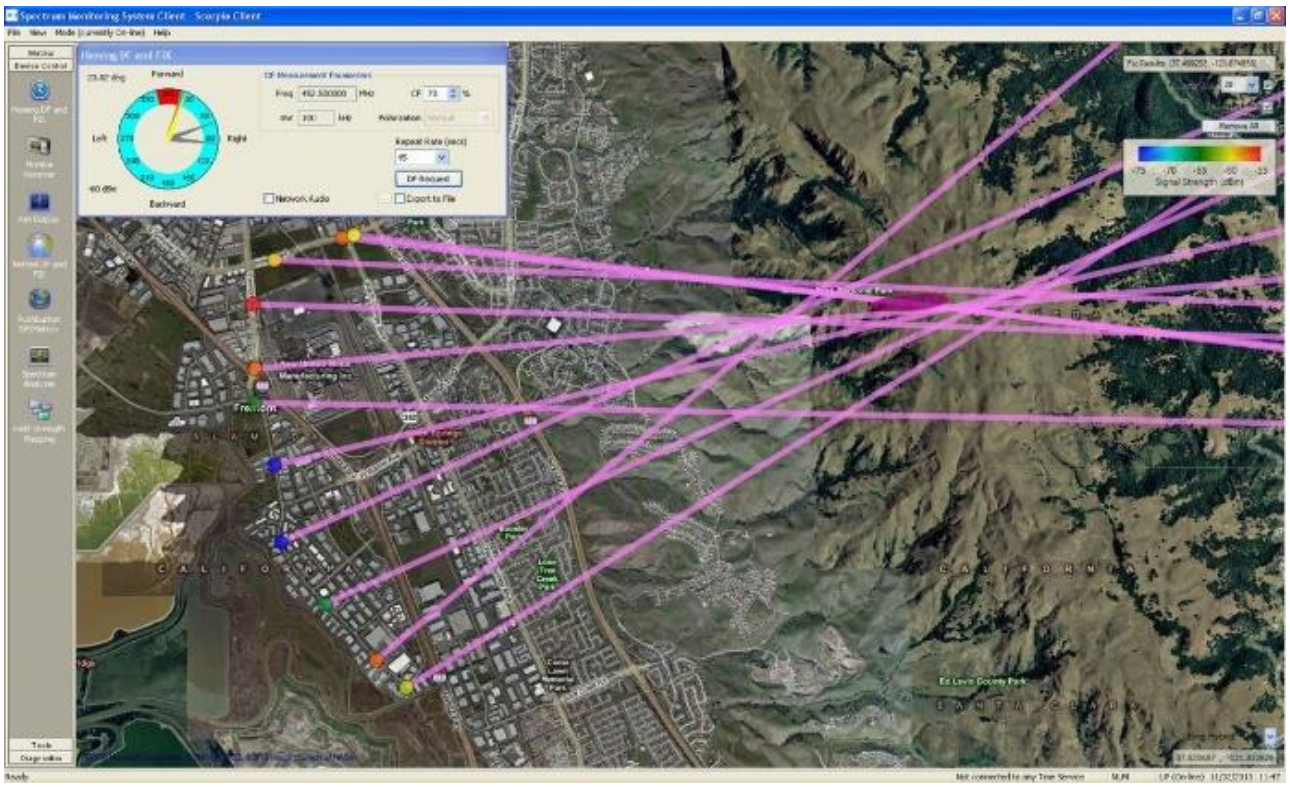
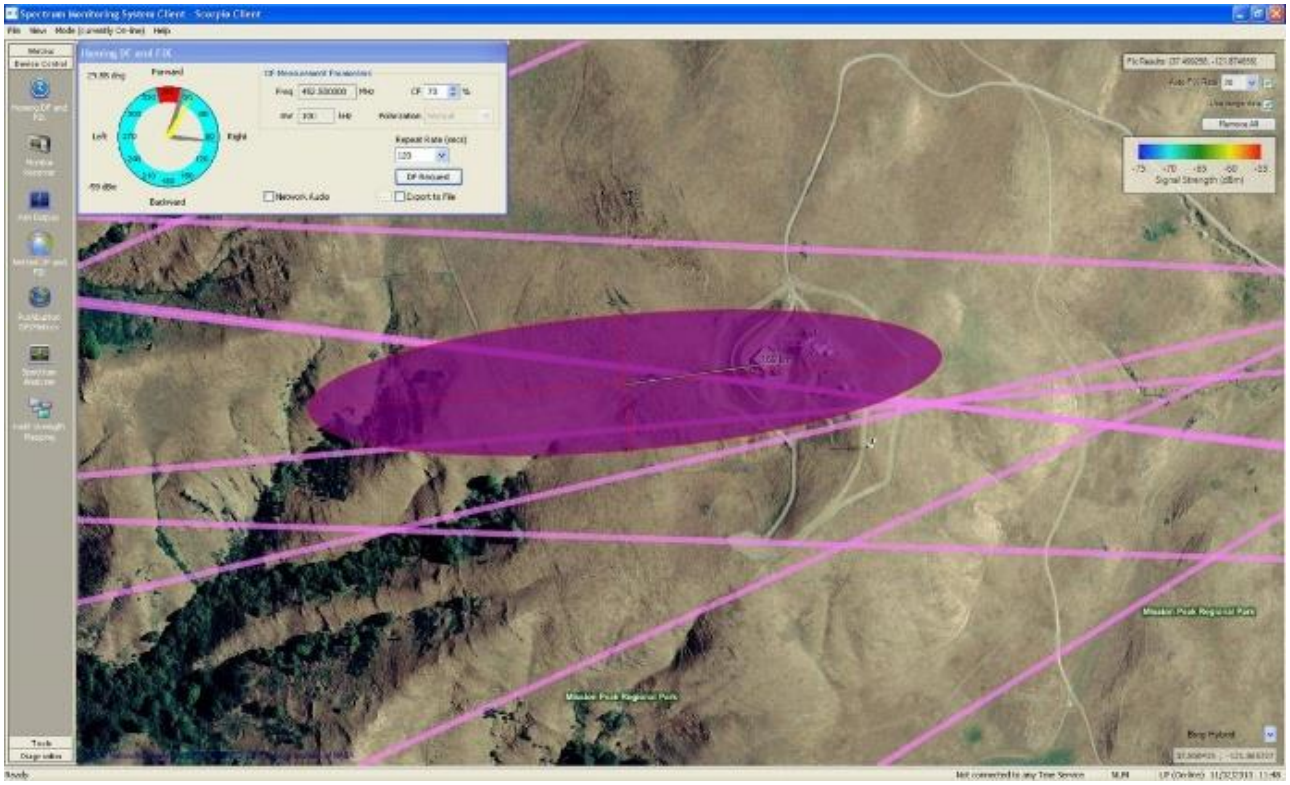


FIGURE 5-75

DF homing approach with error ellipse display: map zoomed to suspected transmitter location (real location is in the building within the ellipse)

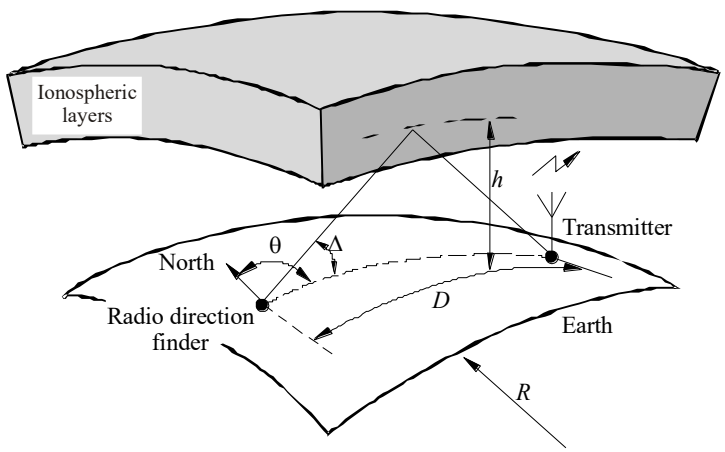


5.7.3.4 Single site location method for HF emissions

The single station location (SSL) system allows determining the geographical position of a transmitter with a single radio direction-finder (see Fig. 5-76). Processing data supplied by the radio direction-finding (azimuth, elevation, position) associated with ionospheric measurements or predictions allow estimating the transmitter distance from the radio direction-finder. The SSL concept thus allows performing the location mission when, for geographical, timing, or availability reasons, a complete triangulation radio direction-finding location system could not be installed. SSL may also be considered as a complement to an existing location system.

FIGURE 5-76

SSL Principle



θ: geographical azimuth
Δ: elevation angle
D: distance
h: virtual reflexion height
R: Earth radius

Spectrum-4.7-21

SSL radio direction-finders simultaneously determine the azimuth and elevation angle of the signal received by the antenna array. Propagation may be by both ground wave and ionospheric wave through multiple paths corresponding to different elevation angles. As a result, the SSL direction-finder supplies an elevation angle evidencing time variations due to multipath interference. Processing algorithms are used to determine elevation values relating to the said multiple paths.

Such processing, associated with ionospheric measurements or predictions, allows estimating the transmitter distance from the SSL radio direction-finder at distances ranging up to 2 500 km (although estimates of transmitter distances greater than 1 000 km or so are subject to significant error due to the low elevation angle of arrival and the geometry of the situation). Association of the azimuth, distance and radio direction-finder position data, allows estimating the geographical coordinates of the HF transmitter.

The basis of the SSL approach is the so-called Classical Method of Range Estimation. This method assumes that the actual HF propagation may be modelled by assuming that reflection takes place from a simple horizontal mirror at the appropriate height. The height of this mirror is derived from a vertical incidence ionogram, as the virtual height at a frequency called the equivalent incidence frequency. The classical method is based on three simple fundamental relations, the Secant Law, Briet and Tuve's Theorem, and Martyn's Equivalent Path Theorem with correction terms to account for the curved Earth and ionosphere.

Limitation of SSL technique

The SSL principle is based on the assumption that the signal is reflected from the ionosphere only once (single hop). Multi-hop propagation leads to calculation of distances that are shorter than real distances. Also, ionospheric height values may be ambiguous. Thus, the reflection may take place from layers of different heights. This may give the result that different distances to the targets are indicated by the SSL system.

5.7.3.4.1 Estimation of the ionosphere height

SSL systems include one or more of the following methods to determine the height of the ionosphere:

– real-time ionospheric characterisation can be obtained from the process of ionospheric sounding. Equipment that performs this process is known as an ionosonde, or sounder. A sounder is able to determine the propagation characteristics of the ionosphere at all frequencies and thereby characterise the ionosphere in the vicinity of the sounder. A sounder requires a transmitter, a dedicated antenna and analysis software;

– calibration with the help of a transmitter with known position (see [Touré, 2004]). This method requires an updated database of the position of the emitters. It is generally not as accurate as SSL results based on ionospheric sounders because calibration on one or a few individual transmitters will not completely characterise the ionosphere at all frequencies as will a sounder;

– Data base with ionosphere prediction files. Some national scientific organisations provide accurate results from complex computations including the solar activity, the propagation layer of the ionosphere, etc. However, the predictions are only an average and do not account for any local, temporary or other propagation effect which can be detected with real time measurements. These predictions are useful when real time information is not available, including cases of propagation with reflection points far from a sounder.

5.7.3.4.2 Localization software

The radio direction-finding software can provide the following elementary results of measurements:

– azimuth (degrees);

– elevation (degrees);

– number of measurements integrated to the average;

– HF level at receiver input (dBm);

– lateral and longitudinal distance errors.

All these data items may be displayed on the operator screen.

5.7.3.4.3 Program generating predictions

In order to be able to determine the position of a transmitter, the location software may include ionospheric predictions files in addition to, or instead of measured ionograms. The prediction software allows generating ionospheric predictions files for a selected geographical site. Modelling is performed in compliance with Recommendations ITU-R P.1239 and ITU-R P.1240.

The ionospheric propagation paths are determined by a radius-plotting program from the knowledge of vertical electronic density distribution. As the ionosphere is an isotropic medium, two characteristic waves exist, which are associated with an angle of the data: the ordinary wave (O) and the extraordinary wave (X). It is then necessary to generate the predictions related to the modes used by the SSL. The prediction file provides, for given time, date, frequency and place, all of the distances corresponding to the requested elevations (histograms).

5.7.3.4.4 Location range calculation

The location software may be used to enter the following parameters:

– elementary DF results;

– current time and date;

– working frequency;

– relevant ionospheric measurements or prediction file.

The different steps of the distance's calculation process for the HF transmitter are:

a) Elevation histograms.

b) Filtering elevation histograms.

c) Determining the packets.

d) Processing "low" elevations.

e) Obtaining ionospheric measurements or generating predictions.

f) Determining the four basic distances.

g) Determining the final distance.

From the four distances a final distance is extracted by resection (see Fig. 5-77).

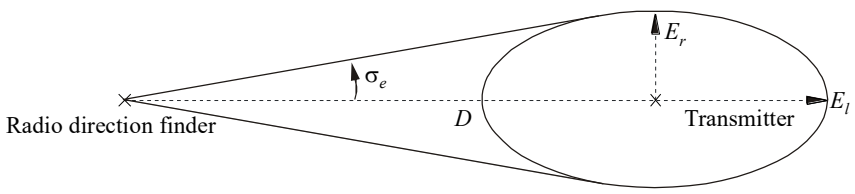
h) Calculating the geographical coordinates.

i) Integrating elementary locations.

j) Location results.

FIGURE 5-77

Distance determination



Spectrum-4.7-22

For each emission, the location calculation can give the following results:

– average azimuth (degrees);

– number of elementary measurements;

– mean HF level;

– radial error;

– longitudinal error;

– geographical coordinates of the transmitter.

The results are accessible by graphic display and printer.

5.7.3.4.5 Validity

The validity of the Classical SSL method relies on the validity of several assumptions that:

1 the Earth's magnetic field can be neglected at certain times;

2 the virtual height obtained from the local ionogram is the same as would be contained at the circuit midpoint;

3 the equivalent ionospheric mirror is horizontal.

For longer circuits, assumption 2) starts to fail, and at some point it is necessary to change over to a ray re-tracing procedure using a model of the ionosphere updated to be consistent with the local ionogram. Such models exist and are in a state of continuing improvement by ionospheric physicists throughout the world, including taking the effects of the Earth's magnetic field from assumption 1) into account. Computational power and speed continue to improve the execution of multi-dimensional ray re-tracing procedures through complex ionospheric models. Existing HF Propagation prediction programs such as Ioncap, *et al*, are useful

for planning purposes but are of limited value in SSL applications since they are based on annual averages and do not take the real-time state of the ionosphere accurately into account.

The assumption 3) that the equivalent mirror is horizontal leads to the largest errors on short circuits. This error depends inversely on the cosine of the elevation angle. In practice, the ionospheric reflecting surface may be tilted by as much as 4° or 5° from the horizontal due to large-scale gradients (such as at sunrise or in the vicinity of the equatorial anomaly) and small-scale gradients (or "tilts") associated with travelling ionospheric disturbances (or "TIDs"). Consequently, for SSL work on short circuits, it is desirable that the ionosonde also be capable of measuring the local ionospheric tilts so that they may be taken into account. However, there is some evidence that measuring tilts does not improve Line of Bearing results [Bramley1953].

5.7.3.4.6 SSL elevation angle

With the exception of taking the Earth's magnetic field into account in determining the value of the equivalent vertical frequency the assumptions that determine the validity of the Classical SSL Method start to fail as a function of range to the HF emitter, primarily at the two extremes of short- range and long-range. From an understanding of why the Classical Method assumptions start to fail, SSL methods have been developed to make valid range estimates at these two extremes. For a discussion of these methods, the range spectrum may be divided into three categories; short-range, medium-range and long-range.

5.7.3.5 Comparison of location methods

TABLE 5-17

Location method comparison

Item	Homing / Standoff	Triangulation	TDOA location	SSL (HF only)
Required number of stations	1 with homing or standoff functionalities	2 for AOA location 3 for unambiguous locations	At least 3 stations are required and additional stations help to solve ambiguity	1
Required material	DF antenna on a vehicle No network required	One direction finder per site Low data rate network to exchange coordinates and AOA results	Data network to transfer digital signals Low requirements for antenna and receivers Shared time synchronization method (usually GNSS)	1 station that measures elevation and azimuth, and an ionosphere characterization method like ionospheric sounder, predication or calibration
Performance depends on transmitter/locations system geometry	Not applicable	Accuracy is better in the centre of the triangle if 3 DF are used Outside the triangle, the location accuracy decreases slowly	Accuracy is the best within the area bounded the receiver sites Outside the triangle, the accuracy decreases to approximate a single line of bearing	SSL is unambiguous for one hop signal only
Performance depends on the bandwidth of the incoming signal	No Requires permanent or long duration signals	Depending on the method used	TDOA may not be suitable for very narrow bandwidth or unmodulated signals	No

TABLE 5-16 (*end*)

Item	Homing / Standoff	Triangulation	TDOA location	SSL (HF only)
Dedicated for mobile or fixed stations	Mobile only	Fixed and mobile	Fixed and mobile; mobile may not be practical depending on data-link requirements	Fixed
Able to solve multipath/multiple source signals	Not typically, since it often uses conventional methods such as interferometers	See Table 5-14 regarding partly-coherent sources	Yes with advanced TDOA processing techniques	See Table 5-14 regarding partly-coherent sources

5.7.3.6 Combination of localization methods

In general, there is no single method such as the ones based on measuring time difference of arrival (TDOA) and angle of arrival (AOA) that will provide accurate location estimation under all circumstances. Each method has its own advantages and limitations in terms of location accuracy.

TDOA location methods generally provide better location accuracy for wideband signals than the AOA-based location method.

However, the TDOA-based methods require relatively more stations than the AOA-based methods to perform location of emitters. For instance, the TDOA-based methods require at least three properly distributed stations for location.

The AOA methods, on the other hand, require two stations for location. However, a small error in the angle measurements will result in a large location error if the station is far away from the transmitter.

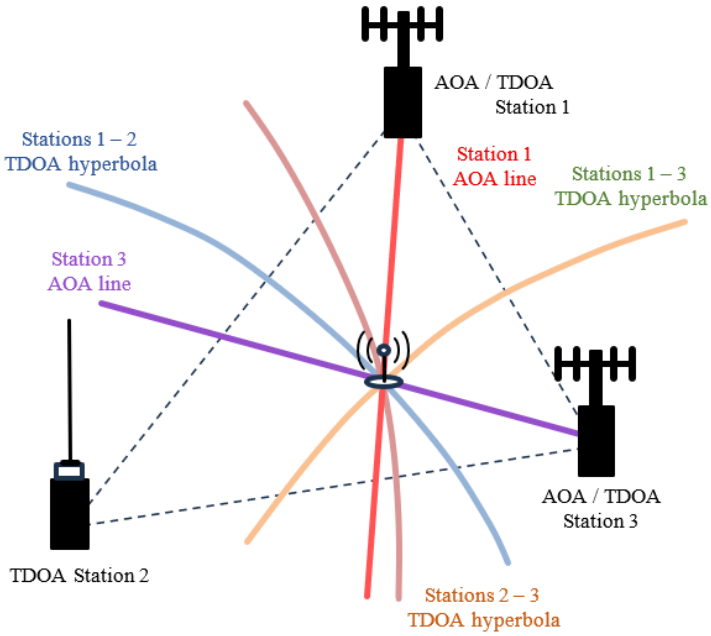
Therefore, to achieve better location accuracy, a combination of two or more location schemes should be considered in order to complement each other.

The location is performed by processing the information available from each station, including AOA measurements, TDOA measurements and station position information.

Combining the AOA method with the TDOA method can assist in eliminating location ambiguity associated with TDOA alone and can enhance location accuracy. This hybrid method is illustrated in Fig. 5.7-30 for the case of two stations equipped for both AOA and TDOA measurements and one station equipped for TDOA measurement.

FIGURE 5-78

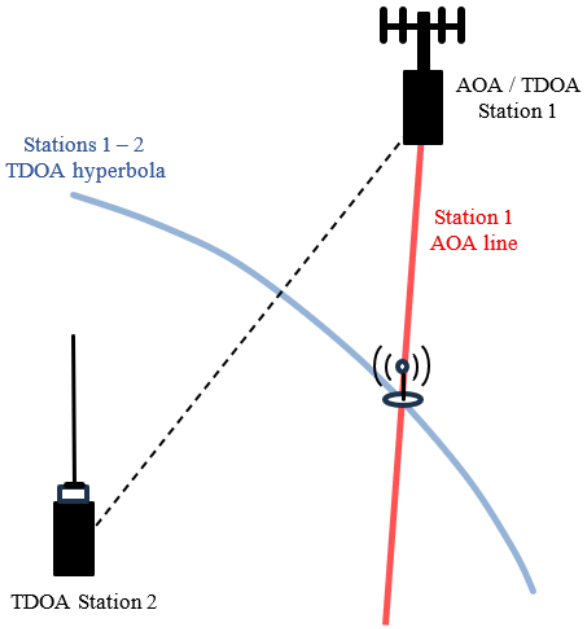
Improved results based on AOA/TDOA combined techniques



The minimum number of stations for which this hybrid method can obtain a location is one AOA/TDOA station and one TDOA station, where the AOA station produces one line of bearing and the two TDOA stations produce one hyperbola and their intersection gives the location estimate, as illustrated in Fig. 5-79.

FIGURE 5-79

Example of minimum (two station) configuration for hybrid AOA/TDOA localisation



More information on the hybrid approach, including real-world examples is given in Report ITU-R SM.2211 as well as Report ITU-R SM.2355 (‘Multi-mode location’ and Annex 2).

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ITU-R Recommendations

NOTE – In every case the latest edition of the Recommendation is encouraged be used.

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Recommendation ITU-R M.489 – *Technical characteristics of VHF radiotelephone equipment operating in the maritime mobile service in channels spaced by 25 kHz*

Recommendation ITU-R M.589 – *Technical characteristics of methods of data transmission and interference protection for radionavigation services in the frequency bands between 70 and 130 kHz*

Recommendation ITU-R SM.854 – *Direction finding and location determination at monitoring stations*

Recommendation ITU-R P.1239 – *ITU-R Reference ionospheric characteristics*

Recommendation ITU-R P.1240 – *ITU-R methods of basic MUF, operational MUF and ray-path prediction*

Recommendation ITU-R SM.2060 – *Test procedure for measuring direction finder accuracy*

Recommendation ITU-R SM.2061 – *Test procedure for measuring direction finder immunity against multi-path propagation*

Recommendation ITU-R SM.2096 – *Test procedure for measuring direction finder sensitivity in the VHF/UHF frequency range*

Recommendation ITU-R SM.2097 – *On-site accuracy measurements of a fixed direction finder system*

Recommendation ITU-R SM.2139 – *Test procedure for determining the accuracy of TDOA systems*

Recommendation ITU-R SM.2140 – *Performance evaluation of mobile direction finders in operational environment*

Recommendation ITU-R TF.767 – *Use of global navigation satellite systems for high-accuracy time transfer*

ITU-R Reports

NOTE – In every case the latest edition of the Report is encouraged to be used.

Report ITU-R SM.2211 – *Comparison of time-difference-of-arrival and angle-of-arrival methods of signal geolocation*

Report ITU-R SM.2125 – *Parameters of and measurement procedures on HF/VHF/UHF monitoring receivers and stations*

Report ITU-R SM.2354 – *Alternative test procedure for measuring accuracy and immunity of direction finder using a simulator*

Report ITU-R SM.2355 – *Spectrum monitoring evolution*

Report ITU-R SM.2356 – *Procedures for planning and optimization of spectrum-monitoring networks in the VHF/UHF frequency range*

Report ITU-R SM.2391 – *The effects of wind turbines on fixed radio direction finders*

ITU-R Handbooks

NOTE – In every case the latest edition of the Handbook is encouraged to be used.

Handbook on Computer-Aided Techniques for Spectrum Management (CAT)

5.8 Signal analysis and transmitter identification

5.8.1 Introduction

Signal analysis is the process of extracting information from a transmitted signal and may be done to characterise a signal (frequency, bandwidth, modulation parameters, etc.), localize it (see also § 5.7), and/or identify the owner (e.g. a station's call sign). The multitude of different digital modulation techniques have made signal analysis a more important tool for radio monitoring services for the purpose of classifying and identifying signals. This also applies to analogue modulated signals as well (see also § 5.6).

The discussion below is related to narrow-band signals such as analogue/digital PMR, but also applies to wideband, pulsed and OFDM modulated signals. Information specific to the analysis of IMT-signals such as 3G, 4G and 5G is found in § 6.3[1].

Signal analysis is often used for identification and is particularly required when the basic tools of spectrum monitoring are not sufficient to identify the source of a signal. It should be conducted by trained monitoring experts using appropriate hardware and/or software. In case there is no equipment and software commercially available for a specific measurement task, a customized software package may need to be created. Some

[1] While care is taken to refer to the official definition of IMT-generations, parts of this document contain material, which refers to the frequently used market names "xG". In general, IMT-2000, IMT-Advanced, IMT-2020 and IMT-2030 are known as 3G/4G/5G/6G, respectively.

commercially available signal analysis packages include the ability to customize the demodulation and decoding process to accommodate variants from industry standard signal formats. There are also many open-source online communities offering demodulation and decoding algorithms to process a wide variety of communication formats. Before making the effort to develop a custom algorithm, tools available from these communities should be researched carefully. Correlation analysis, cryptography and steganography are also relevant to this subject. Some of these related techniques are discussed elsewhere in this Handbook and depending on national laws, may be restricted.

The matter of station identification is addressed in Article **19** of the RR (Identification of Stations). No. **19.1** states that: "All transmissions shall be capable of being identified either by identification signals or by other means.". This is often achieved by a direct identification embedded in the transmission like a call sign, the stations name, the operating agency, a maritime mobile service identity, an official registration mark, an aircraft identification, a selective call identification number or other clearly distinguishing features that can readily be recognised internationally. Depending on the radio application, the call sign – or parts thereof – may be assigned by different organizations / administrations. Recommendation ITU-T E.212 is an example of one procedure in the assignment of identification numbers. As an example, some codes developed for maritime mobile and maritime mobile-satellite services are shown in Annex 1 and Annex 2 of this section.

RR No. **19.1.1** also recognizes that the transmission of identifying signals for certain radio systems (e.g. radiodetermination, radio-relay systems and space stations) is not always possible. In this case, the class of emission can be used as a form of identification.

Transmitter identification might be required to support monitoring tasks such as:

– identification of spectrum users;
– determination of spectrum utilisation;
– compliancy with the licence conditions;
– spectrum use efficiency;
– detection and identification of illegal use;
– detection and identification of interferers;
– localising the origin of signals.

When a transmitter's identification is not indicated within the signal, analysis and localization needs to be performed to properly classify the emission and identify the signal's source.

Signal analysis is not necessarily a complex task. For example, listening to AM or FM broadcast stations with the goal of identification is also a signal analysis task. Several different traditional methods are available to identify a signal:

– using the call sign or embedded signal identification data
– locating the transmitter
– matching the signal parameters with the license database or allocation table
– performing technical identification using signal parameters to classify the type of transmitter
– signal aided identification

This section describes these methods in detail. Further guidance can be found in § 5.6, in Recommendation ITU-R SM.1600 and other publications as noted in this section's bibliography. Readers should be aware that the working methods described herein evolve at speed, especially when considering methods laid out in Chapter 4. A glimpse of the future can be seen in Report ITU-R SM.2542 – Next generation spectrum monitoring – proactive, autonomous and data-driven. However, the information contained herein shall allow the reader to understand the fundamentals of how these machines work.

5.8.2 Capabilities needed to perform signal analysis

A monitoring receiver as described in Chapter 3 is needed for signal acquisition and analysis either in real time or as a post process. It is usually necessary for the receiver to have IQ-recording capabilities for the signal of interest, especially for signals that are intermittent, pulsed, or short in duration. Important considerations for these recording devices are the acquisition bandwidth, the dynamic range, and the maximum recording time.

When the signal(s) is recorded, a vector signal analysis, and/or decoding software can be used to perform many different forms of analysis and mathematical functions to help classify the type of transmitter and identify the source. These forms of analysis are described later in this section. In many situations, the analysis software needs the ability to re-centre, zoom (in frequency), and trim (in time) the recording to properly isolate the signal of interest.

The ability to view the signal in time, frequency, and modulation domains make the analysis more effective and efficient. However, some signal formats require more advanced processing consisting of a combination of mathematical tools and signal features. In the rest of this section, basic and advanced measurements are described. Basic measurements are those which could be deduced from the signal external and internal parameters. Advanced measurements of a signal are related to techniques available only after successfully demodulating of the signal such as decoding. There are both real-time as well as off-line signal decoding tools available on the market.

These systems and the associated software may include:

– specific decoders for a variety of signal types commonly found on certain frequency ranges like HF, VHF/UHF;

– parametric (manual) decoders or demodulator-decoders with or without measurement capabilities;

– automatic demodulators-decoders with signal recognition and measurement capabilities.

When real-time analysis fails, operators need to process a recording of the signal with off-line analysis tools which may include:

– signal analysis tools for the time, frequency and phase domains;

– adjustable / programmable demodulators;

– bit-stream analysis, e.g., tools to discover the code structure and determine the correct alphabet input;

– tools for development of mathematical operations based on the code structure which can configure a programmable decoder for future real-time decoding.

When the decoding and alphabet selection is successful, the operator will get text which is often encrypted, except (in some cases) during the transmission of the station's identification.

Signal analysis and transmitter identification could be performed either manually or as an automated operation with a dedicated system. Any automated system should be open and flexible in both hardware architecture and software functionalities to adapt to new signals and apply new techniques. These systems often employ so called 'classifiers' to determine signal parameters and potential matching demodulators. More of that and some techniques applied therein can be found in Recommendation ITU-R SM.1600.

5.8.3 The process of signal analysis

Signal analysis is used to extract information from a signal that helps determine the type of emitter (referred to as signal classification) and to identify the user. In all cases, the simplest method of signal identification through analysis that yields the correct result should be used. The signal analysis process is described by the steps below and in Fig. 5-80.

1 Extract the signal external parameters. These include the centre frequency, occupied bandwidth, format (single- or multi-carrier), spectral shape and the received signal strength. This information can be used to research licensed emitters within a radius from the monitoring station that match the extracted parameters. The spectral shape can also be used to correlate against known emitters with a unique spectral profile.

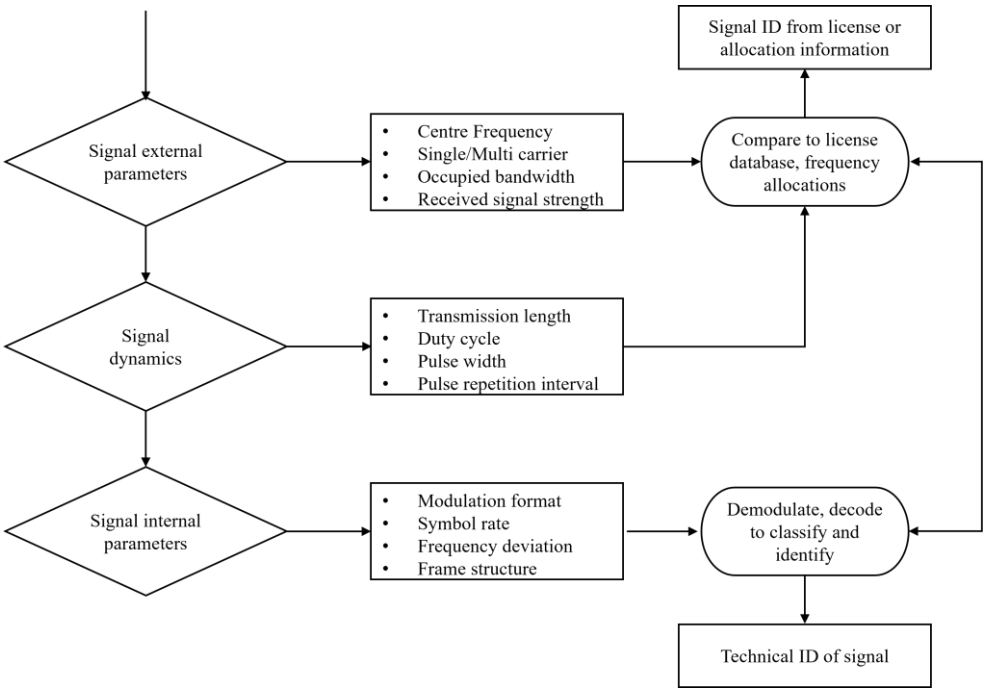
2 Determine the signal dynamics (time domain behaviour). This includes the transmission length, and if the signal is pulsed, the pulse width and pulse repetition interval. Signal dynamics can also be described in terms of start/stop time, occupancy, and duty cycle.

3 Extract the signal internal parameters. These include the number of modulation states, modulation format, symbol rate, frequency deviation and any other details related to the structure of the information coded in the signal. These parameters can be used to demodulate and potentially decode the signal, extracting original content or the unique station identification. They also provide additional information to support making an informed determination about the type of transmitter.

4 Finally, an analysis of the demodulated data can be performed. Decoding may be necessary to process the data, resulting in the extraction of information from the demodulated data stream. If demodulation is not possible, the signal should be classified by its parameters (frequency, bandwidth, modulation format, symbol rate, etc.). Once this information is available, the type of transmitting device can be estimated and located through AOA or TDOA methods for positive identification.

FIGURE 5-80

Signal analysis process



The following pages give an example of the analysing process. A signals external and internal parameters are used along with databases and location measurements to identify a signal of interest.

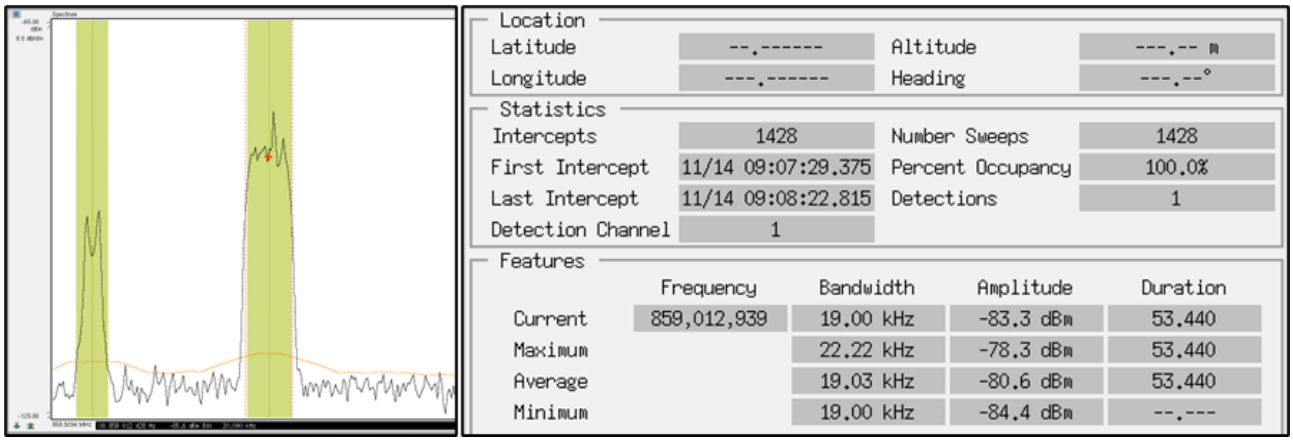
5.8.3.1 Analysis of signal external parameters

In Fig. 5-81, a spectral trace clearly displays two signals above the noise floor of the receiver. The trace marker is manually positioned on the signal to the right with a centre frequency of 859.012428 MHz, with a bandwidth of approximately 20 kHz. This is the signal of interest for identification.

The assigned frequency for this signal is most likely 859.0125 MHz and that can be used for a license search along with the location of the monitoring station, angle of arrival (if available), and the received signal strength. By assuming a transmitter power, the received signal strength can be used to estimate the distance to the transmitter with an appropriate path loss formula (e.g. free space, rural, urban). This distance can be used in the license search. If the license search produces a result whose technical and operating parameters are in line with the signal of interest, the transmitter has potentially been identified.

FIGURE 5-81

Signal external parameters of signal of interest



The spectral trace also shows vertical grid lines indicating that the monitoring software automatically detected these signals, extracted the external parameters. The line spacing corresponds to the calculated bandwidth. For the signal on the right, the results of this automated detection and feature (or parameter) extraction are shown in the table to the right of the spectral trace.

These spectral metadata include much of the information needed for identification of the transmitter, including centre frequency, bandwidth and amplitude level. It also includes information on the signal dynamics including duration, occupancy, time of the first and last intercepts, the number of intercepts and detections during the current observation interval. In this example, the occupancy is 100%, indicating this signal is most likely a control or broadcast channel.

This information, along with the location of the monitoring station, can be used for a license search. The information in Fig. 5-82 is from an online radio reference utility. A search was done in the three counties close to the monitoring station. The highlighted row indicates that the frequency 859.0125 is assigned to the user NxT (actual user is not shown) and is part of a TETRA radio network.

FIGURE 5-82

Online licensee reference data on signal of interest

System Name: NxT
Location: Regional, xx, xx, xx
County: 7 Counties
System Type: TETRA Standard
System Voice: Tetra Digital
Last Updated: July 22, 2025, 02:08 am UTC
System Notes:
The system is not simulcast - sites will only carry traffic when users are affiliated to that specific site.

Sites and Frequencies

*(c) are control channel capable frequencies

Site	Name	County	Frequency assignments	
025 (19)	Barnegat	Ocean	856.3875	857.3875
029 (1D)	Galloway	Atlantic	855.5625	857.2625
031 (1F)	Mays Landing	Atlantic	855.4125 c	858.4125
034 (22)	Atlantic City	Atlantic	858.2875	859.8375
035 (23)	Woodbine	Cape May	854.3375	858.0125
036 (24)	Cape May	Cape May	857.6875	859.0125
042 (2A)	Northfield	Atlantic	854.0375	854.5875
055 (37)	Little Egg Harbor	Ocean	858.3875	860.3875

The online radio reference also provides a map (see Fig. 5-83) showing the location of the transmitter (site 036 shown pinned) and coverage information (shown as the shaded circle). Based on the map, the monitoring receiver is inside the coverage area and should receive the signal with positive SNR. At this point, localization techniques could be used to estimate the location of the transmitter to determine if the signal of interest is originating from the location provided by the database.

FIGURE 5-83

Online licensee reference map showing emitter location and coverage

To verify the location of the transmitter, a series of TDOA measurements were made as shown in Fig. 5-84. Three sensors were used, two fixed (MON1 and MON2) and one mobile (MOBILE). The fixed sensors are toward the south end of the peninsula. The mobile sensor travelled from south to north while making TDOA measurements. The first measurement (left hand side of figure) shows a coarse line of bearing telling the driver the emitter is to the north. The second measurement (middle of figure) shows convergence of the TDOA measurement but with poor geometric dilution of precision (GDOP) resulting in significant positional error. The third measurement (right hand side of figure) has the best GDOP under the circumstances with the best likelihood of being close to the transmitter of interest.

FIGURE 5-84

Sequence of three TDOA measurements to locate a TETRA transmitter

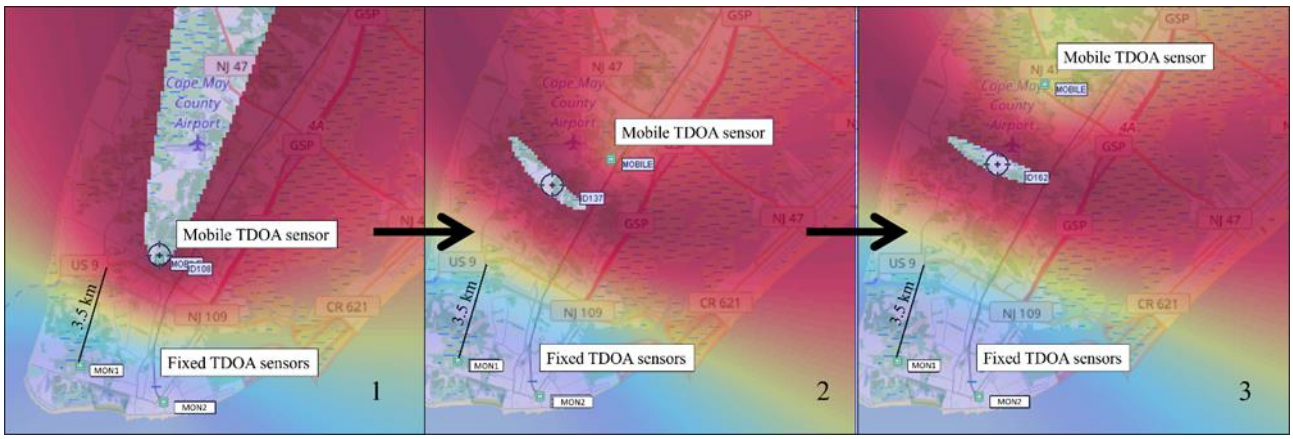
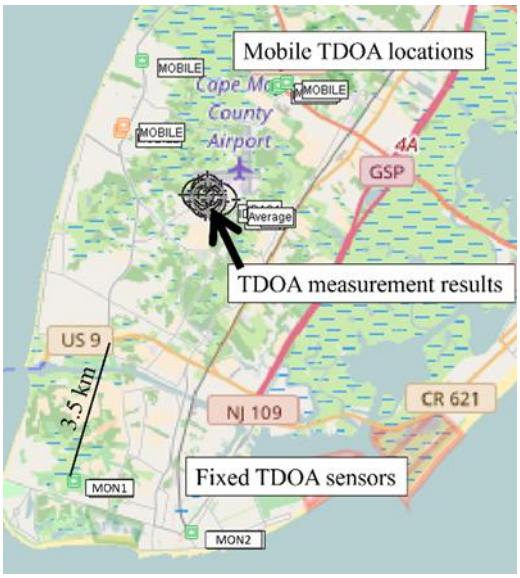


Figure 5-85 shows several results from the measurement campaign with good GDOP and solid correlation. Based on these results, the transmitter has been successfully located, and the results agree with the information found in the license database and online reference data.

FIGURE 5-85

Summary of results from TDOA measurement campaign on signal of interest



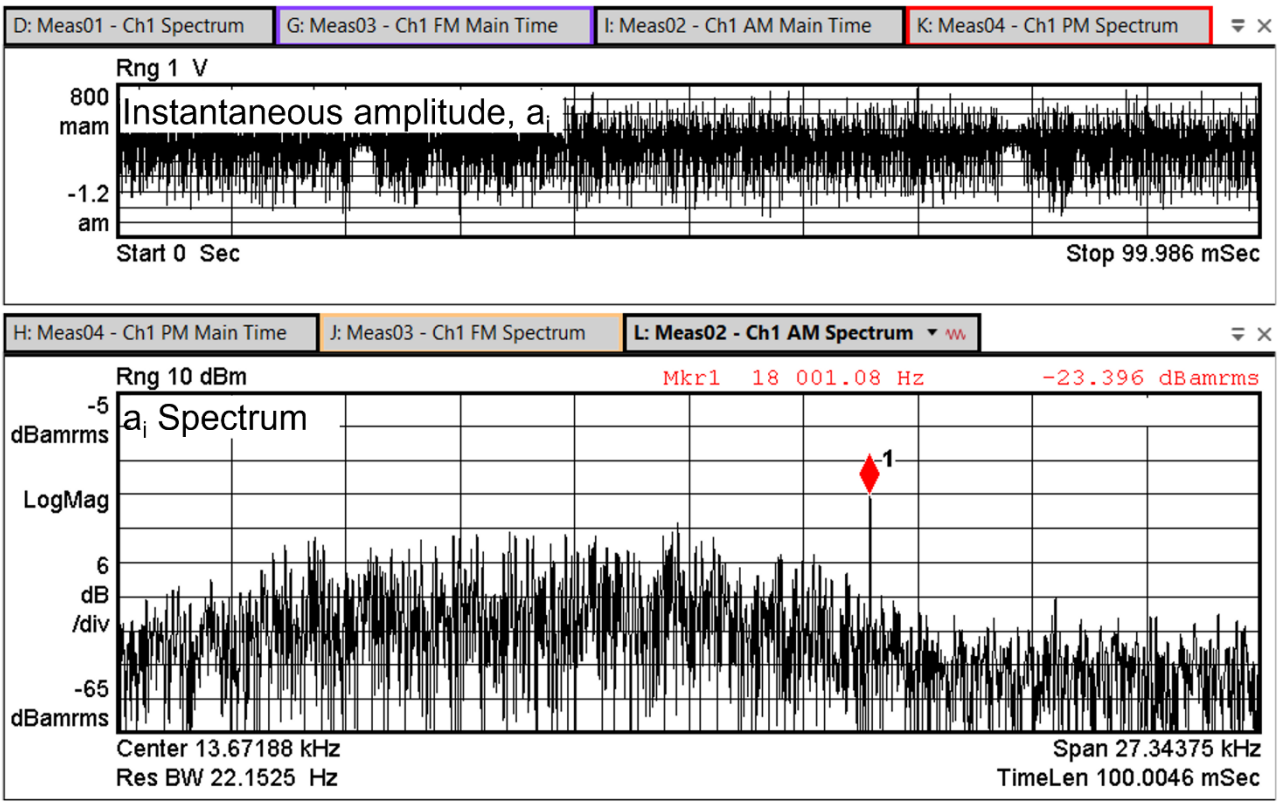
Based on what has been learned about this transmitter, it could be considered to be positively identified. The next step, however, is to confirm the signal internal parameters are in line with the characteristics of a TETRA system. This requires an understanding of the modulation characteristics including the format and symbol rate. An IQ recording of the signal was made with the monitoring equipment and, in the next section, will be used by different software tools to help with the analysis.

5.8.3.2 Analysis of signal internal parameters

The AM spectrum shows the frequencies associated with the instantaneous amplitude variations (AM time) on the signal occurring over time. Digital modulations can cause periodic amplitude variations related to the symbol rate. Using a VSA software tool to analyse the IQ recording (see Fig. 5-86), the amplitude variations during a 100-millisecond interval can be seen in the upper trace. The lower trace is the spectrum of the data in the upper trace, and it shows a clear peak at 18.001 kHz noted with the diamond-shaped trace marker. This is most likely the symbol rate of the transmitter and is in line with one of the symbol rates typically used in TETRA systems (18 kHz).

FIGURE 5-86

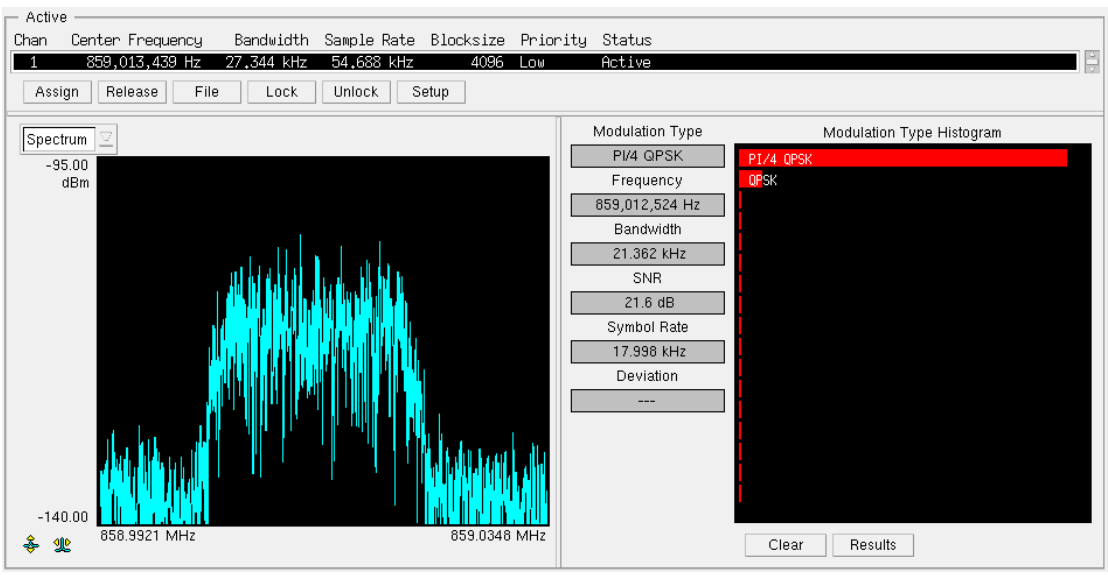
Discovery of the symbol rate using the spectrum of instantaneous amplitude (AM spectrum)



To validate this discovery, a modulation classifier is used to examine the same IQ recording. The results are indicated in Fig. 5-87, and they agree with the conclusion from the peak in the AM spectrum regarding the symbol rate. It also estimates the modulation format to be Pi/4 DQPSK. This provides the settings needed for demodulation of the signal in the VSA software and further confirming the type of transmitter. When working with a new signal format, it is advised to use more than one software tool to validate the results of the internal parameter measurements.

FIGURE 5-87

Using a modulation recognizer to discover format and symbol rate

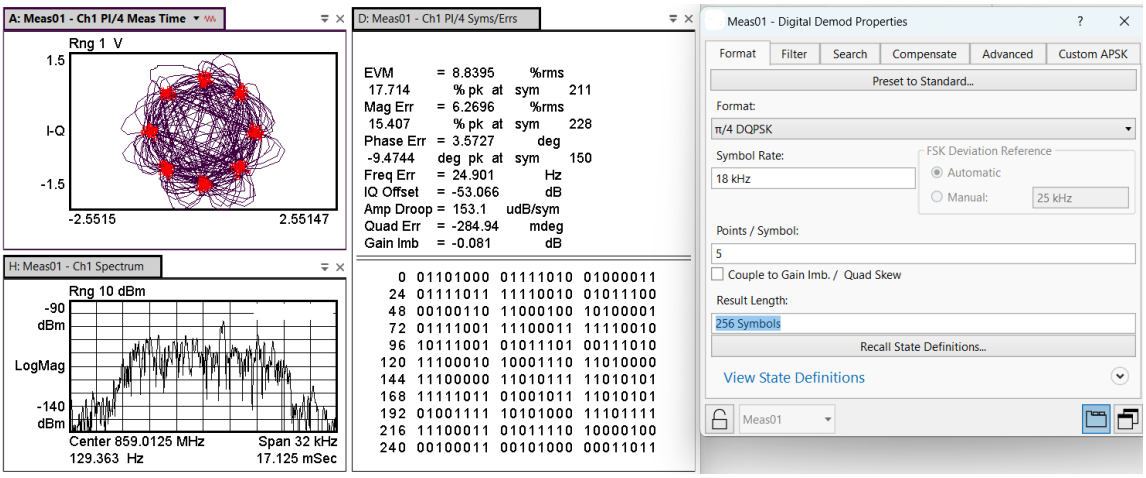


5.8.3.3 Demodulating the signal

Having validated the symbol rate and modulation format of the transmitter, the VSA software can be configured to demodulate the signal by entering the correct digital demodulation properties as seen on the right-hand side of Fig. 5-88. In some cases, the symbol filters roll-off factor might need manual optimization to reduce the error vector magnitude. At this point, the signal has successfully been demodulated, located, confirmed to be fully in line with the type of signals associated with TETRA, and can considered to be parametrically identified.

FIGURE 5-88

Demodulation of the TETRA recording using VSA software



The application of the correct baseband filter with proper roll-off factor (alpha or α) is very important for successful demodulation of a digital signal as it opens the eyes in the eye-diagram and gives a clear view in the constellation diagram.

Baseband filters limit the occupied bandwidth, while reducing the inter-symbol-interference (ISI). Different modulation schemes require different filter types, based on their sensitivity to phase and amplitude variations. Examples of baseband filters commonly found in VSA software include:

– Root raised cosine (RRC) or raised cosine (RC), which are commonly to minimize ISI. They are typically used for linear modulation schemes in which the signal's IQ-vector must periodically through the origin of the constellation diagram (BPSK, QPSK, n-QAM);

– Gaussian filters are used for modulations that employ a constant envelope (no zero-crossing in the constellation diagram), where they minimize the spectrum's sidebands (MSK, GFSK);

– Rectangular filters are often used for basic modulation formats (ASK, PSK, FSK), where bandwidth efficiency is not a priority.

The filter roll-off factor, α, has a numeric range between 0 to 1 and effects the quality of demodulation. A low value maximizes bandwidth efficiency but increases requirements for timing precision with a price of a slower time domain response. Conversely, a high value leads to a wider bandwidth but is more tolerant to timing jitter. While the time domain response is faster some overshoot or ringing can occur, which can typically be seen at the edges of the constellation diagram. As the shape of signals power spectrum reflects the baseband filters shape, one might get good guesses one the used filter type. Additional information regarding baseband filtering can be found in § 5.6.4.3.

5.8.3.4 Decoding the signal

The final step to guarantee the signal has been positively identified involves decoding the signal to read identifying information such as a Site number, Cell ID, call sign, etc. In this example, the IQ-recording was loaded into a decoding software package that was able to extract the Site number (36) for the TETRA transmitter. The decoded message from the TETRA signal operating at 859.0125 MHz is shown in Table 5-17.

TABLE 5-17

Output of a TETRA decoding session

StartTime	04.09.2020 01:14:14.959
Tetra:BurstType	SB (Note 1)
Country Code (MCC)	310
Network Code (MNC)	1
Colour Code	36
Country Code	310 Network Code: 1 Colour Code: 36
Tetra time	2020-09-04T01:14:14.959Z
Tetra:BurstType	NDB (Note 2)
Tetra:PDUType	SYSINFO (Note 3)
Location Area	36
Main Carrier Frequency	857687500 Hz

NOTE 1 – BurstType SB indicates a synchronization burst.

NOTE 2 – BurstType NDB indicates a normal downlink burst used for testing and analysing the performance of TETRA base stations.

NOTE 3 – The PDU protocol data unit type "SYSINFO" is a broadcast message containing essential network parameters. In this case, the location area indicates the base station site. It also includes the frequency of the main carrier – which is associated with 859.0125 MHz in the reference database in Fig. 5-82.

5.8.3.5 Summary of analysis

This example intents to show the steps involved in a real-life situation. Site number 36 aligns with that found in the online reference for the TETRA system of interest and provides a positive identification of the transmitter. The signal analysis process has been fully completed on this emission, starting with the most basic external parameters of centre frequency, bandwidth, and received signal strength. These parameters were used to initiate a database search to match the frequency with known licensees. A localization was made to validate the location of the transmitter and match it to the database information. Next, the signal internal parameters were analysed and found to align with those of the identified service. Finally, the signal was decoded, and the identifying site number was extracted and found to match the database entry. License databases or online resources providing relevant information are not available in all regions, but using a combination of analysis tools, a signal can be characterized, classified, localized, and ultimately, identified.

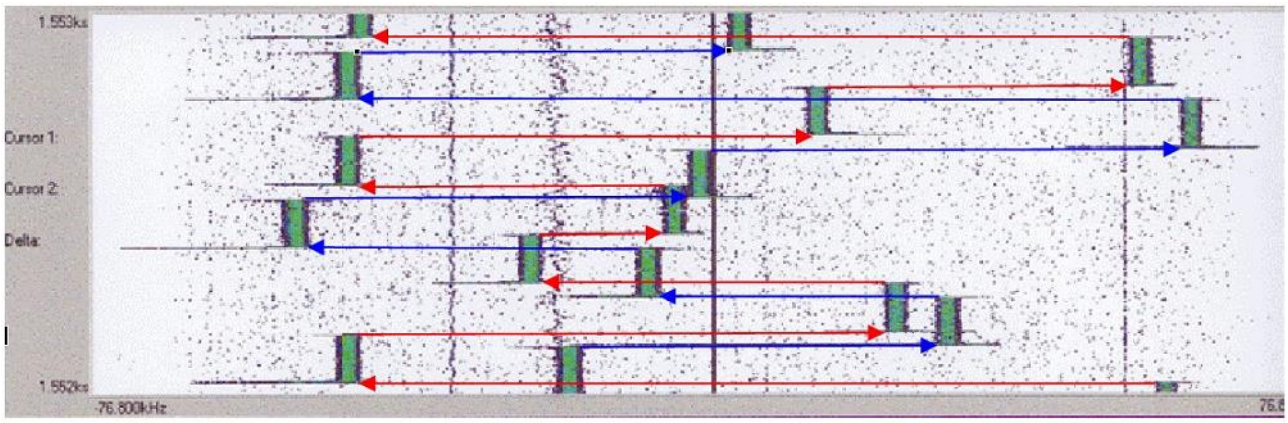
5.8.4 Signal dynamics and analysis in the time domain

The term signal dynamics describes behaviour in the time domain and is characterized by expressions such as transmission length, occupancy, duty cycle, pulse width, pulse interval, pulse repetition frequency, TDM interval, guard interval, and hop rate. Time domain analysis is an essential element of signal analysis tools and is used to understand the dynamic variations of signals not continuously being transmitted. An example of time domain analysis using a spectrogram to display frequency agile signal characterisation is illustrated in Fig. 5-89.

In this example, the time domain is used to discriminate two different signals with different frequency hopping patterns. Each pattern (red and blue arrows) has been identified manually. Such operations may also be performed automatically. Other parameters may be derived from this display including the hop durations, hop frequency, and the list of frequencies used by each transmitter.

FIGURE 5-89

Example of frequency hopping signal characterization

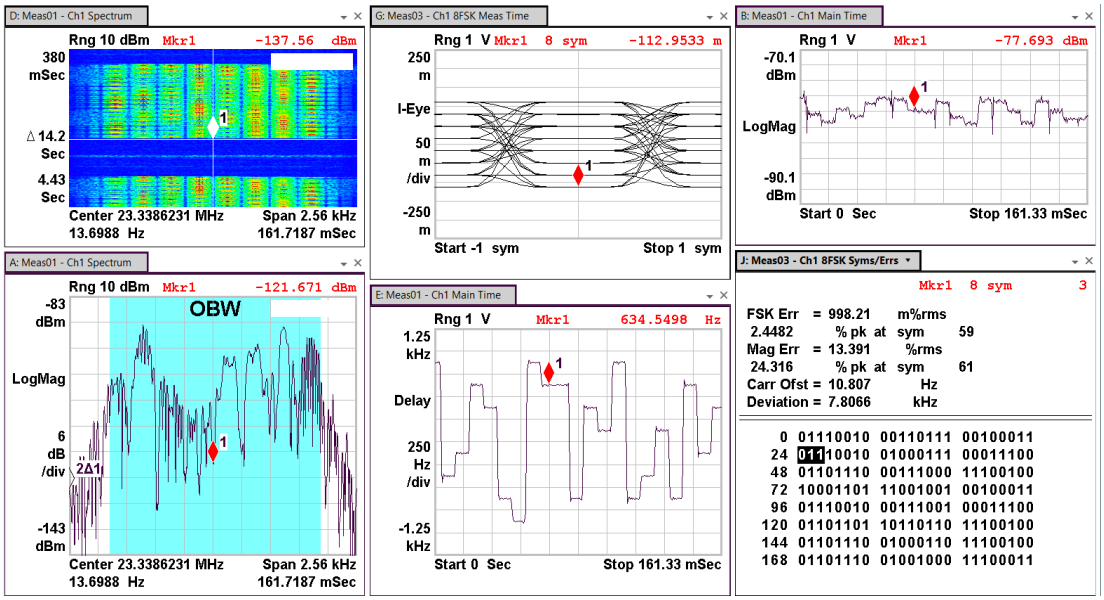


Spectrum-4.8-06

After such an analysis, the conformity to a standard can be checked and the signal demodulated using a conventional demodulator. If it is not possible to demodulate the signal, parameters as instantaneous frequency, amplitude and phase can be used to make a technical description of the signal. This analysis requires software capable of isolating individual hops in both frequency and time to extract basic parameters and inspect the signal internals. VSA software can simultaneously display both frequency and time domain analysis making the characterization of signal dynamics and external/internal parameters possible. Figure 5-90 shows analysis of a short duration 8FSK signal in which the signal external, internal, and dynamics are clearly displayed. This fully classifies the type of transmitter responsible for the signal and clears the way for decoding to identify the user.

FIGURE 5-90

Signal analysis of external, internal parameters and signal dynamics



Common radar signals can be described by its time domain parameters, and a frequency hopper by its hopping pattern, duration, and frequency. The dynamics of communication signals usually fall into the categories of control or traffic channel, uplink or downlink. Broadcast services are often considered to be on the air continuously, but on close inspection, can have short intervals when the signal is paused due to time domain separation of programming. These features can all be discovered using time domain analysis to understand signal dynamics.

5.8.5 Advanced tools for signal parameter extraction

Although basic signal parameters may be determined by graphical means as described above, some mathematical tools may also be used. For example, estimation of the 2nd and 4th order moments of the signal can provide a precise determination of carrier, symbol rates and chip rates for regular single-carrier, multi-carrier signals, and pseudo-noise/CDMA signals. Multi-carrier digitally modulated signals can, in most cases, be identified by the determination of certain key technical parameters such as the symbol duration (T_s), the guard time (T_g), and the number of subcarriers as described in § 5.6. In § 5.6, some "blind" techniques are described which can be very useful for parameter extraction on wideband or complex signals.

For characterisation of the modulation scheme of the signal, the following methods/tools can be used (after the determination of the carrier frequency and the time behaviour of the signal):

– a symbol synchronisation display such as eye diagram and/or constellation of phase diagram;

– a polar representation for the linear modulation types (validation of synchronisation, determination of the constellation points and the transitions between symbols);

– histogram representations for the phase or frequency modulations (validation of synchronisation, determination of the number of subcarriers).

Some of the algorithms for the extraction of technical parameters and estimations of digital modulation parameters are summarised below in Table 5-18. Note that many of these methods are also useful to characterise analogue signals.

TABLE 5-18

Some methods to extract technical information depending on the modulation of the analysed signal

Modulation	Measured parameter	Analysis tool or technique
Any	Presence of signal (positive SNR at receiver required)	High resolution spectral trace
	Presence of signal (positive SNR optional)	Cross-correlation of instantaneous amplitude A_i with reference signal
	Presence of signal (positive SNR optional)	Cross-correlation of time-synchronous IQ acquisition of the signal from two or more spatially separated receivers using a TDOA algorithm.
	Carrier frequency, subcarrier frequencies	High resolution spectral trace or spectrogram with trace marker(s)
	Emission bandwidth	High resolution spectral trace with occupied bandwidth or *x* dB markers
	Number of subcarriers or tones	Spectral power density
These techniques apply more specifically to the case of amplitude dominant modulations.		
OOK, ASK	Carrier frequency	Spectrum correlation and moments method
	Keying duration and transmission length	Amplitude versus time trace (AM time) using spectrum analyser in zero-span or spectrogram
	Symbol rate	Histogram of duration of instantaneous amplitude
		Peak in the spectrum of instantaneous amplitude A_i (AM spectrum)
	Number of states	Histogram of instantaneous amplitude, A_i

TABLE 5-18 (*end*)

Modulation	Measured parameter	Analysis tool or technique
These techniques apply more specifically to the case of frequency dominant modulations.		
FSK	Carrier frequency	Centroid of frequency peaks observed in the spectral trace or spectrogram
		Carrier may be directly measured in the spectral trace or spectrogram if present at the start of transmission
	Frequency deviation or shift	Difference in frequency peaks in the spectral trace or spectrogram using delta trace markers
	Symbol rate	Peak in the spectrum of instantaneous frequency (FM spectrum)
		Dominant peak in spectrum of instantaneous frequency raised to power N in N-FSK (e.g. $N = 2, 4, 8$)
		Spectrum of zero crossing of instantaneous frequency, F_i (see § 5.6 for description)
	Number of states	Histogram of instantaneous frequency, F_i
	Number of subcarriers or tones	Histogram of instantaneous frequency, F_i
	Symbol synchronisation	Eye diagram A_i/F_i and histogram display frequency, F_i
FSK, OFDM, COFDM	Number of states	Spectral power density
These techniques apply more specifically to the case of phase dominant modulations.		
PSK, QAM, CPM	Carrier frequency	Spectrum raised to power N (= 2 (PSK), 4 (QAM), or 1/h for CPM)
		Spectrum correlation or moments method
	Symbol rate	Spectrum of signal modulated domain (like frequency, phase) raised to power N (= 2 or 4)
	Number of states	Histogram of instantaneous phase, Φ_i
		Constellation diagram/vector diagram
	Symbol synchronisation	Eye diagram I/Q, A_i/F_i and vector diagram
CPM	Symbol synchronisation	Constellation diagram and histogram display of frequency, F_i and phase, Φ_i

Figure 5-91 provides an example where the symbol rate of 1.2 kHz of a 2 FSK signal is obtained from the instantaneous frequency F_i raised to the second power.

FIGURE 5-91

Determining the symbol rate of a 2 FSK signal by its instantaneous frequency raised to the second power

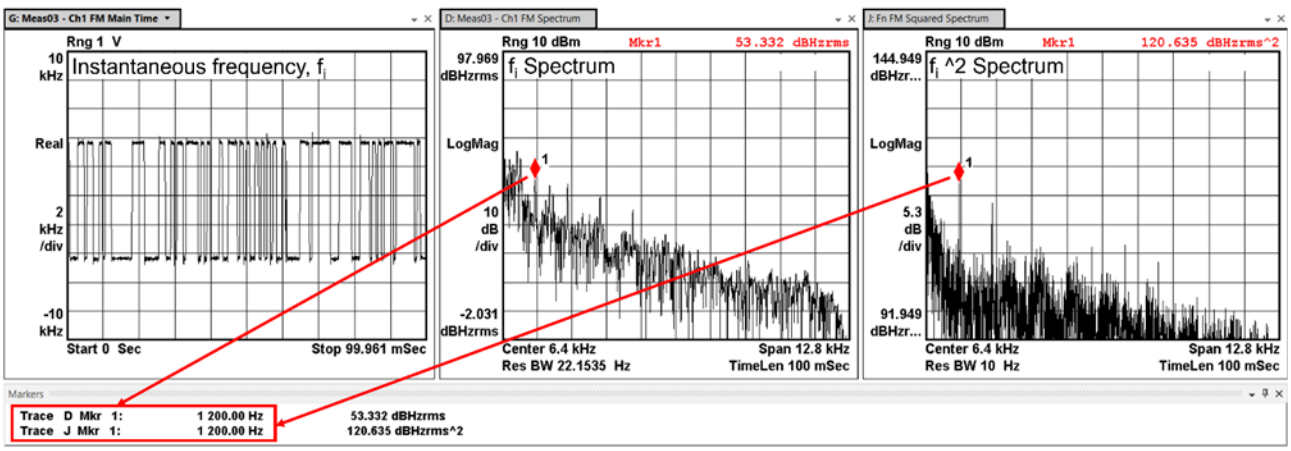
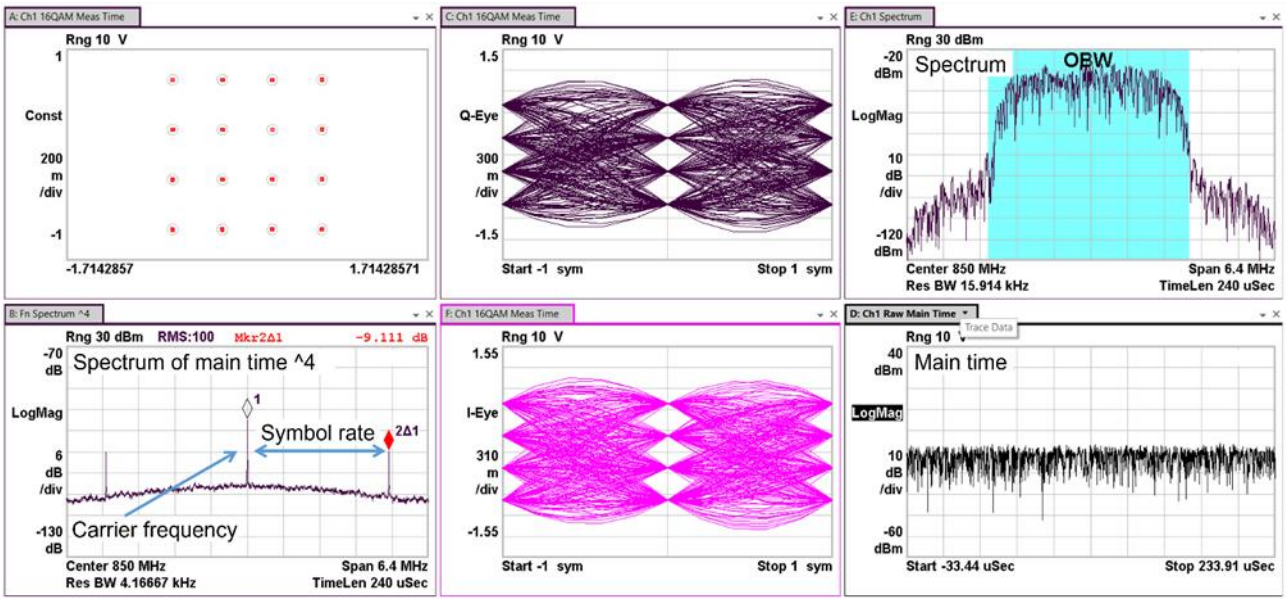


Figure 5-92 shows advanced techniques described in the table above used to extract technical parameters from a 16-QAM modulated signal. The traces on the right show the spectral trace with measurement of the occupied bandwidth and the main time. The centre traces show the eye diagrams of I and Q which provide insights into the symbol synchronization and the effects of the baseband filter on the demodulation – which in this case is nearly ideal. On the left are the constellation showing the number of states (16) and the spectrum of the main time raised to the fourth power which reveals the carrier frequency (at 850 MHz) and the symbol rate (2.5 MSymbols/second). This set of information provides a very good technical characterization of the signal of interest.

FIGURE 5-92

Determining technical parameters of a 16-QAM modulated signal using VSA software

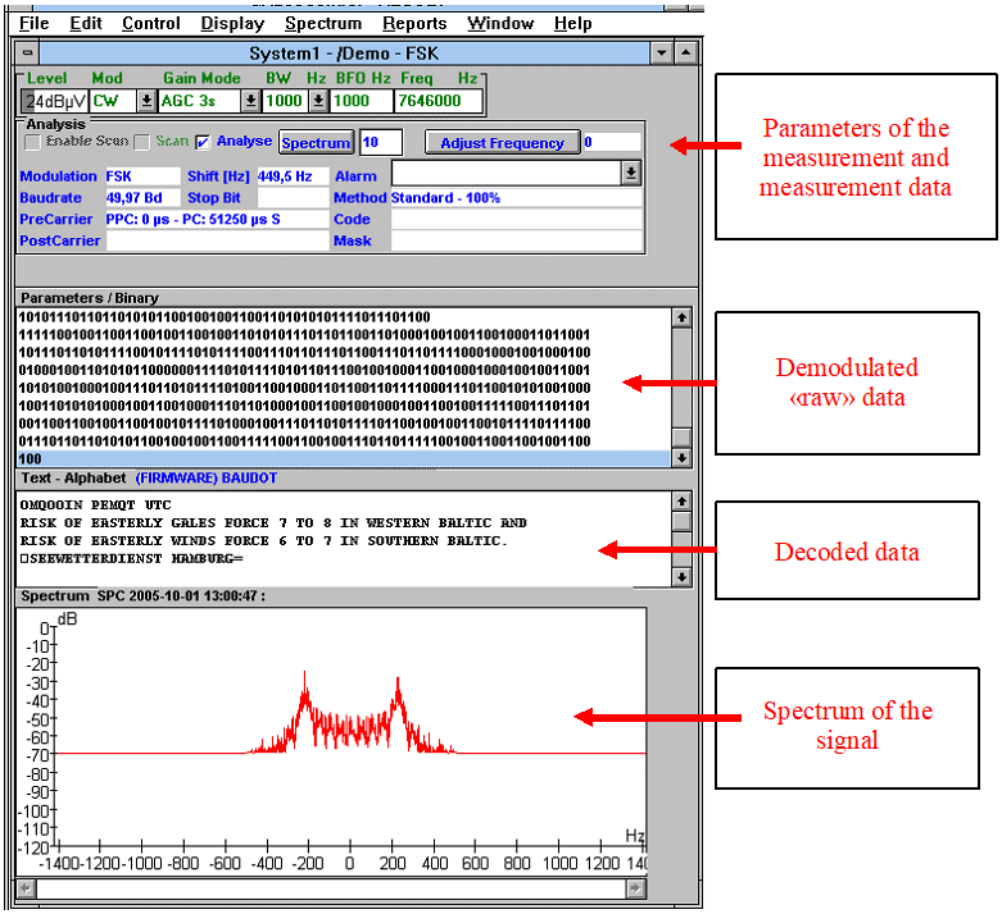


One of the last steps is the extraction of the message content. A demodulator should have a bit stream analyser applying correlation techniques on the bit stream for determining the used coding scheme. The bit stream should be mapped to different information units such as an alphabet.

Figure 5-93 illustrates an example of a digital demodulator with bit stream analyser display for one of the more conventional modulation types (FSK).

FIGURE 5-93

Example of a digital demodulator with bit stream analyser and decoder



Spectrum-4.8-10

5.8.6 Correlation techniques

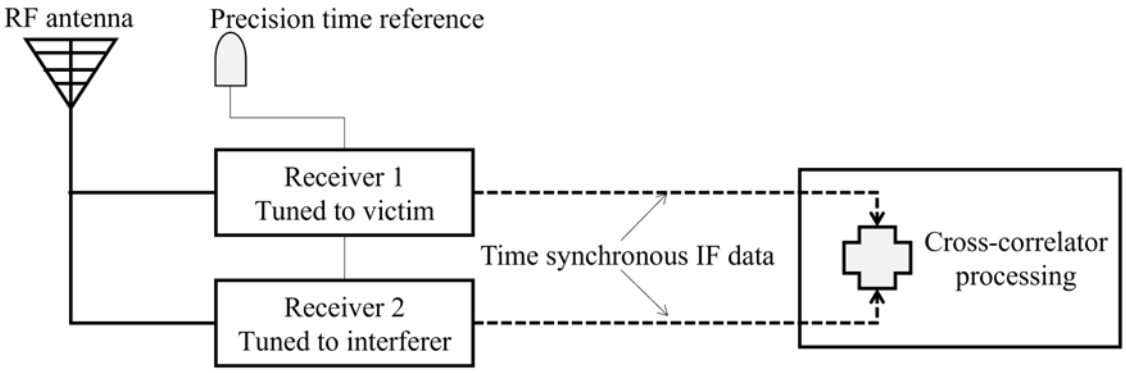
Interference and other special cases of concern present challenges to the monitoring service as the transmission may be intermittent or the exact frequency may not be known so the transmission may not be easily observed. In these cases, it may be necessary to use equipment to record a wide bandwidth of the spectrum presumably including the transmission of interest, so a trained operator can perform the analysis later.

5.8.6.1 Cross-correlation techniques for interference analysis

The cross-correlation method can be employed to investigate how interference is formed and to identify the interferers. A simplified diagram is given in Fig. 5-94.

FIGURE 5-94

Cross-correlator for interference analysis



Two separate receivers are used; one is tuned to the interfered (victim) signal and the other to the suspected interferer. In this application, the receivers are collocated and the IF data – whether digital or analogue must be time synchronous to support the cross-correlation process. Cross correlation effectively compares the two signals in the time domain looking for a match in the structures. Random noise is eliminated from the results. If the victim signal contains a copy of the interferer, a positive correlation will result. By calculating the correlation coefficients between the IF signals or the demodulated signals, an identification of the interferer may be obtained. The following types of interference can be detected:

– spurious emissions;

– intermodulation emissions;

– spurious and intermodulation channels of a receiver;

– effects of blocking and cross modulation;

– adjacent channel interference.

Correlation techniques are not only applicable for interference investigations but also applicable for other monitoring tasks such as emitter location by TDOA.

Detailed information about the correlation method can be obtained from Report ITU-R SM.2355-2, Annex 1.

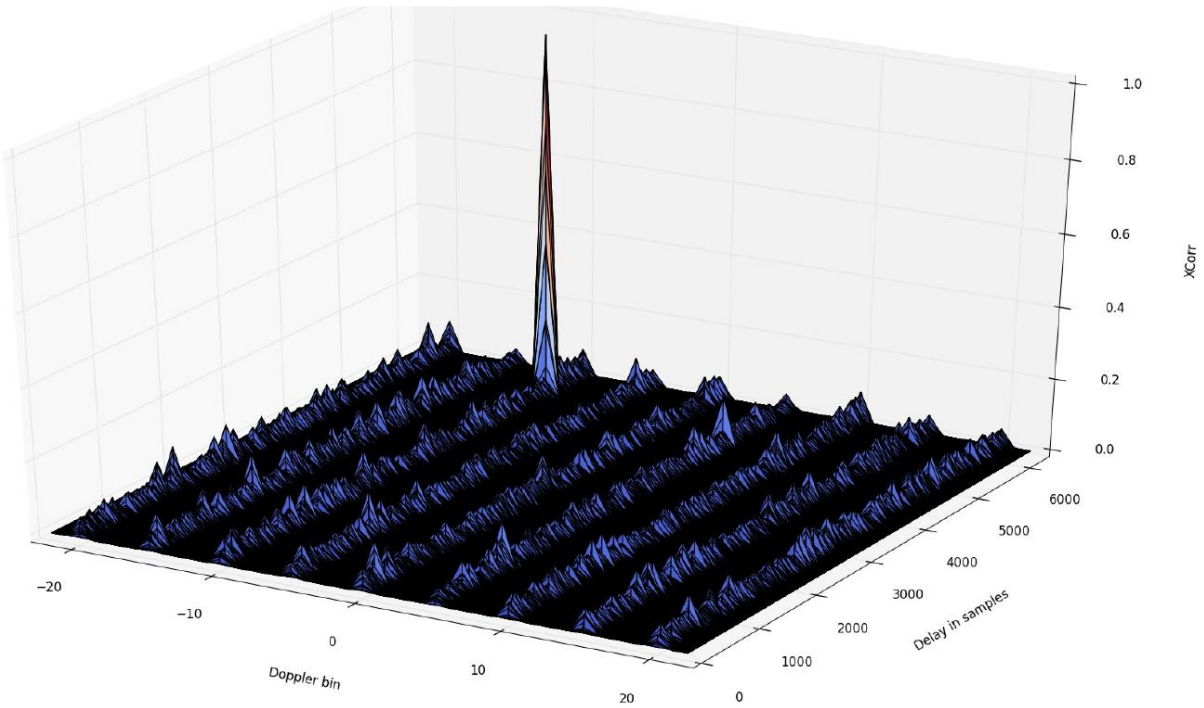
5.8.6.2 Intercorrelation with a test signal

Another efficient way for identification and measurement of signals can be performed using intercorrelation techniques with test signals as part of the search. The peak value of the intercorrelation of the analysed signal with a test signal makes it possible to detect the presence of a signal similar to the test signal inside the analysed signal. Additional information can easily be obtained such as estimation of the channel's impulse response, the verification of demodulation quality, and information on the channel or timeslot occupancy. The method can also be used on synchronisation to pilot sequences for decoding and identification purposes. A test signal from a database can be used or the test signal can be generated using a reference signal. Techniques like this can be applied to conventional (analogue) systems as well.

An example of such an analysis is shown in Fig. 5-95. Therein, a known code sequence is correlated against a received signal by searching within a frequency- and time grid. The result of that cross-correlation process stands out as a dominant peak on the vertical axis. This not only confirms the presence of the signal, but also the frequency and time offset relative to the receiver parameters. FFT techniques enable computationally efficient processing of such an algorithm. For that, the figures frequency axis is divided in bins.

FIGURE 5-95

Example of a correlation analysis: search along a frequency- and time grid



5.8.7 Traditional signal identification methods

During monitoring observations, the parameters describing each detected signal may be stored in a signal database. This database, including abstractions for submission to the ITU BR in accordance with RR Article **16**, can be designed in the desired format to support the operations of the monitoring service. These databases simplify the search for vacant spectrum and help with the identification of interference. RR Article **5**, Frequency allocations (including the footnotes), the IFL, and lists of known stations transmitting press bulletins are examples of sources helpful in defining the fields of a database.

Handbooks compiled by monitoring organisations often contain information that cannot easily be stored in files and can be very useful for signal identification purposes.

5.8.7.1 Call sign recognition

Such techniques allow, with a single parameter measurement, to identify an emission and a transmitter.

Formation of call signs

The formation of call signs is derived from an international alpha-numerical series allocated to countries in accordance with the Table in RR Appendix **42**. Additional information concerning the formation of call signs within the various services may be found in Section III of RR Article **19**, as well as in Resolution **13 (Rev.WRC-97)**. An example of these transmissions is given in Annex 1 to this Section 5.8.

Radiotelegraphy systems

Transmissions may consist of a single channel, a time division multiplex system (TDM), a frequency division multiplex system (FDM) or a combination thereof. In single-channel systems the call sign may be transmitted in Morse code or in a teleprinter code with the same type of modulation as used for traffic on that particular channel. Often, bit-interleaving and / or bit scrambling techniques are used for additional robustness of the signal, like forward error correction. In FDM systems, where many different traffic channels are radiated, it is sometimes arranged that one channel is used for maintenance purposes. Most often, this is the only channel used for identification purposes, especially if arrangements are made on the traffic channels to secure the communications using scramblers or encryption devices. Engineering channels are usually left open.

Radiotelephony systems

The most common method of identification is to transmit the call sign in clear speech; however, in single-sideband telephony transmission, a method of superimposing the call sign with Morse code using amplitude modulation on the reduced carrier may be used.

Mixed-service radio systems

A mixed system typically uses a single-sideband emission for one or more telegraph channels arranged in time or frequency-division multiplex, and one or more telephone channels modulating the same radio-frequency carrier, which may be at full, reduced or suppressed amplitude.

In mixed-service channels, any of the methods indicated for identification of time-division multiplex or single-sideband frequency-division telegraph stations may be used for identification purposes.

5.8.7.2 Transmitters with no call sign

When no call sign is transmitted, identification may be performed either by characterising the received signal with a monitoring receiver or spectrum analyser as described in the sections above or by localising the transmitter (see § 5.7 on direction finding and location).

In some cases, demodulation might reveal the identity the signal. However, speech scramblers are often used by maritime mobile and military services. These devices rearrange the speech spectrum in frequency and time so that standard receiving equipment will not produce "clear speech" without specialised processing. Cryptographic techniques are commonly used in transmitting equipment, making it difficult to extract any of the original speech or content from the received signal.

5.8.7.3 Parametric identification

Parametric identification deals with the parameters of a signal. A parametric identification for public standard systems can be performed with three steps:

1 The technical parameters of the modulation are measured using methods described in § 5.6 for analogue and digital signals.

2 Then, when all the parameters have been measured, an analysis is performed to recognise the modulation among a list of possible candidates.

3 Once the type of modulation is recognised, a further step is to demodulate the signal using the estimated modulation parameters. The demodulated signal may then be used for recognition of audio characteristics or digital codes.

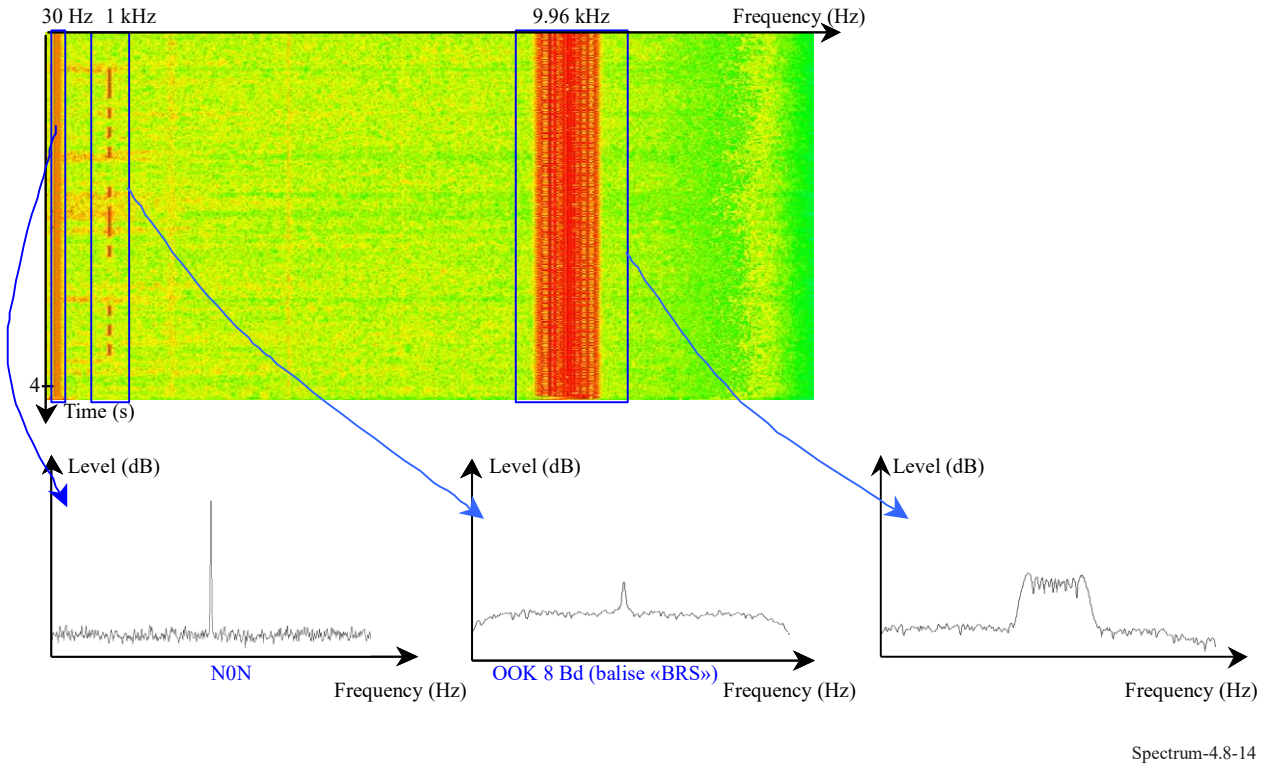
Limitations of parametric identification

The parametric identification method has several limitations because the result of the parametric identification is a list of technical parameters with no indication on the type of system involved (cellular, aeronautical ...).

This drawback is illustrated in Fig. 5-96 for the case of a VOR signal (VHF Omnidirectional Range for aeronautical radionavigation). A VOR signal consists of three sub-carriers, each of them modulated with different schemes. For such a signal, the parametric identification only characterises the three signals but is not able to identify the system as a VOR system. In this specific example, referring to the frequency allocation table would reveal that the signals are for navigation aids based on the frequency, providing information on the system creating the transmissions. Decoding or locating the transmitter would be required for positive identification.

FIGURE 5-96

VOR signal identification



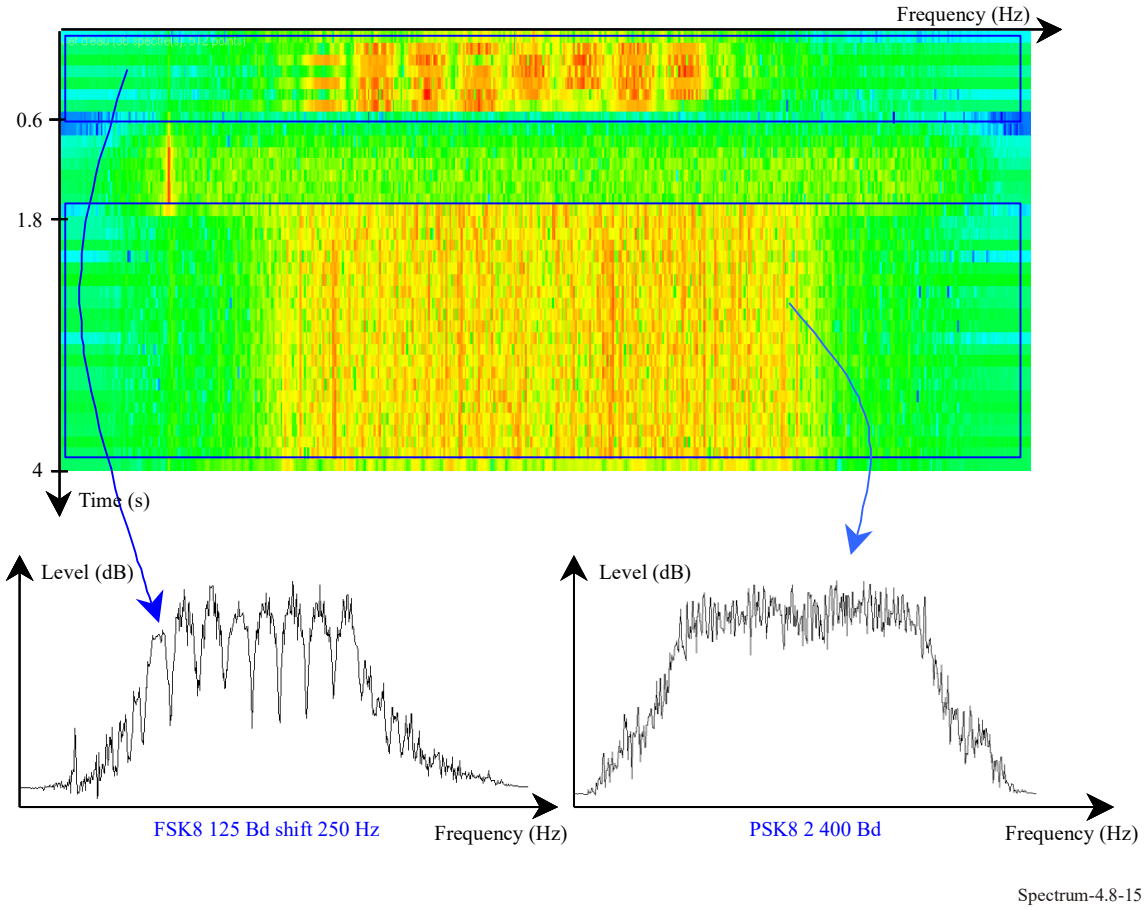
As a first step, the fact that all three emissions belong to the same emission can be proved by using spectrum recorders and narrow band or wide band direction finders. Signals with the same azimuth and simultaneous on/off switching suggest a common source. As a second step, with this knowledge the identification process can continue.

Furthermore, no result is provided if the signal is not on the list of the modulations supported by the method and the incoming signal should have a minimum duration to allow a complete analysis and measurement of all modulation parameters (type of modulation, number of states, symbol rate, etc.).

For example, as shown in Fig. 5-97, when the transmission is composed of two consecutive signals, each having a different modulation, the parametric identification method is not able to identify the system: even if the process can recognize technical details about the individual signals, it still lacks the ability to put the partial results into a suitable context.

FIGURE 5-97

Signal with modulation changing with time



Parametric identification of an analogue signal

The identification of an analogue signal can be done in 4 steps:

Step 1: Adjust measurement setup in a suitable way.

Step 2: Check whether the signal is a known modulation which can be made audible or visible by demodulation.

Step 3: identify speech using the long-term characteristics of speech by calculations and histogram of the variance of the peak value of the signal.

Step 4: Simultaneously with the preceding methods:

– view panoramic representations and time vs. frequency display of the signal to determine its nature (AM, SSB, FM, etc);

– consult radiocommunication signal database;

– perform measurements previously described to determine modulation parameters:

- carrier and subcarrier frequencies in the case of frequency division multiplex protocols;
- occupied bandwidth;
- modulation characteristics (amplitude depth, frequency and phase deviations), measured according to ITU-R Recommendations in force.

Parametric identification of a digital signal

Three steps can be used to identify a digital signal:

Step 1: modulation parameters measurement (see further to § 5.6).

Step 2: when modulation parameters have been measured, the constellation is plotted, then compared to the theoretical constellation.

The Error Vector Magnitude (EVM) may be used to adjust parameters of the measurement in order to obtain the optimum constellation.

Step 3: Demodulation can begin with the correct parameters.

5.8.7.4 Signal aided identification

In this method, a database of public standard system signals (called models) is used as a reference. Every model in the database is composed of a set of parameters. Signal aided identification is based on comparison of the structure and characteristics of the signal under test to the structure and characteristics of candidate models in the database. The chosen model is the one providing the best matching ratio with respect to the signal under test.

A model may be described by the following parameters:

– centre frequency range and channelisation (many standard systems have a published frequency/channel plan);

– occupied bandwidth range (this may be an expected bandwidth; some tolerance is needed to differentiate between the channel table and actual bandwidth);

– spectral shape;

– time behaviour (continuous, bursted emission, TDMA slots, etc.);

– modulation format and symbol rate;

– coding method;

– identification information (call sign, identification number, etc.).

Signal aided identification provides the following improvements:

– improved focus of search in models of interest to the operator;

– faster search results with higher quality;

– improved sensitivity, because it is a comparison between a known reference model and the signal of interest;

– ease of adding new system characteristics to the candidate model database.

However, some constraints appear:

– each candidate system is required to have a model in the database in order to be identified;

– the more candidate system models to be compared, the greater the computing time required.

Annex 1 to Section 5.8

Selective calling in the maritime mobile and maritime mobile-satellite services

The description of the procedure is referred to in RR Article **54**, No. **54.2**.

1 Formation of ship station and coast station selective call numbers

Call numbers of ship stations consist of five-digit numbers. Call numbers of coast stations consist of four-digit numbers. See Recommendation ITU-R M.257. Each digit is represented by an audio frequency from 1 124 to 2 110 Hz according to the following table:

Figure	1	2	3	4	5	6	7	8	9	0	Figure repetition
Audio	1 124	1 197	1 275	1 358	1 446	1 540	1 640	1 747	1 860	1 981	2 110 Hz

The time duration of each tone = 100 ms. A selective call number of a ship transmitted by a coast station lasts 500 ms followed by an interval of 900 ms after which the ship's selective call number is repeated. (Recommendation ITU-R M.257.)

For ship stations using narrow-band direct printing (NBDP) in accordance with Recommendation ITU-R M.476, the five-digit identification is converted to four-character in accordance with Recommendation ITU-R M.491 (Annex 1). For coast stations, the four-digit number is also converted to a four-character code.

According to Recommendation ITU-R M.257 "the sequential single frequency selective-call system (SSFC) may be used for calling ships until the system is superseded by the DSC system described in Recommendations ITU-R M.493 and ITU-R M.541" (see RR No. **54.2**).

2 Maritime mobile service identities in the maritime services

The identities must comply with the provisions of RR Article **19**, Nos. **19.108-19.117**. Maritime mobile service identities (MMSI) are formed of nine digits which are transmitted over the radio path. As an example, the 9-digit code constituting a ship station identity is formed as follows:

M1 I2 D3 X4 X5 X6 X7 X8 X9,

M1 I2 D3 represent the maritime identification digit (MID) and **X** is a figure from 0 to 9 The MID reflects the nationality of the station. For instance, MID 203 is allocated to Austria, and MID 244 to the Netherlands.

Narrow-band direct printing is not only used in accordance with Recommendation ITU-R M.476 but also in accordance with Recommendation ITU-R M.625. Recommendation ITU-R M.625 on NBDP is compatible with Recommendation ITU-R M.476 and uses the 5-digit identity (converted to a four-character code) as well as the 9-digit code. This 9-digit identity number of the ship may be translated to a 7-signal identity conforming to Annex 2 to Recommendation ITU-R M.491. For example, the 9-digit identity 364775427 is converted to "PEARDBY" which is, in the case of calling this ship station by a coast station, transmitted in three blocks of three characters in simplex TOR mode as follows:

Block 1:	P	RQ	E
Block 2:	RQ	A	R
Block 3:	D	B	Y

RQ = request or signal repetition (YBBYYBB)

3 Maritime mobile service identities in the maritime mobile-satellite service

The identities must comply with the provisions of Section VI of RR Article **19**. Ships complying with the International Convention for the Safety at Sea and other ships equipped with automated radiocommunications, including digital selective calling (DSC) and/or carrying alerting devices of the global maritime distress and safety system (GMDSS) should be assigned ship station identities, as set forth in RR Article **19**, Nos **19.100-19.126**, in accordance with Annex 1 to Recommendation ITU-R M.585.

NOTE 1 – RR Article **19**, Nos **19.117** to **19.126** were suppressed by WRC-07.

4 Automatic transmitter identification system

Some countries use an automatic transmitter identification system (ATIS) for RR Appendix **18** frequencies for inland waters, and for satellite uplink video transmissions. The systems provide an automatic transmission of the identification at the end of each transmission and periodically during transmissions. An ATIS sequence may be based on Recommendation ITU-R M.493, or on Recommendation 7 of the Regional Basel Agreement. The radio call sign may be converted to a ten-digit identity.

Z1 M2 I3 D4 X5 X6 X7 X8 X9 X10,

where:

Z: represents the figure 9 and shall be used for inland waters only.

MID: identification digits in accordance with the RR, Article **19**.

X5 to **X6**: shall contain a figure representing the second letter of the call sign, wherein 01 represents A, 02 represents B etc.

X7 to **X10**: shall contain the number of the call sign.

For example, the call sign PC 8075 is converted to: **9 2 4 4 0 3 8 0 7 5**.

5 EPIRB identities

Emissions of emergency position indicating radiobeacons (EPIRBs) participating in the COSPAS-SARSAT system, consisting of low polar-orbit satellites and transmitting on 406.025 MHz, include the 9-digit identity. The 406 MHz EPIRB may also be supplied with a 121.5 MHz homing beacon transmitter. The COSPAS-SARSAT system is a worldwide operating system.

The 1.6 GHz EPIRB (L-band EPIRB or INMARSAT-E) also uses this 9-digit identity and makes use of the INMARSAT system. Because INMARSAT uses GSO satellites positioned over the equator, this is not a global covering system. Coverage is limited to the areas between 70° North and 70° South latitudes for practical applications.

The means of identification in the maritime services are various. *Recommends* 6 of Recommendation ITU-R M.585 states “that any future international automatic maritime telecommunication system should be designed to use the 9-digit ship station identities on the radio path”.

Annex 2
to Section 5.8

Supplementary code characters, sixth and seventh symbols

The sixth character indicates a group of systems. The following characteristics and groups are in use:

Morse	A
Asynchronous (start-stop)	C
ARQ systems with non-interrupted pulse train	E
Burst type ARQ-systems	F
Twinplex	H
Unknown (but number of bits in a frame are known)	J
Forward error correcting	K
Multitone	M
Radionavigation and location	N

The seventh character indicates the system within one the above-mentioned group and is an exact indication of the system in the group. This makes it possible to define 26 different systems within each group (e.g. group A, group C, group E). For example, the seventh character B indicates the system Telex Baudot with group C, ARQ E3 in group E.

The Table below provides examples for some known systems:

CODE	NAME	ALF	BITS	DETEC/CORR	M/CYC	DUR/DIS/NUM
	Morse	Morse				
C-	START STOP					
CB	telex Baudot	ITA2	7.5			
CC	telex Russian	ITA2_RUS	7.5			
CD	telex Arabic	ITA2_ARAB	7.5			
CK	telex ASCII	ITA5	10	parity		
E-	ARQ pulse train					
EA	ARQ-1000 duplex	ITA2_P	7	parity	RQ	4 5 8
EB	ARQ-E3	ITA3	7	m/s = 3:4	RQ	4 8 3
EC	342 TOR 1 kan	ITA3	7	m/s = 3:4	RQ	4 8 3
ED	342 TOR 2 kan	ITA3	7	m/s = 3:4	RQ	4 8 3
EE	342 TOR 4 kan	ITA3	7	m/s = 3:4	RQ	4 8 3
EK	ARQ-N	ITA2_P	7	parity	RQ	
EL	POL-ARQ	SITOR	7	m/s = 3:4	RQ	
EM	TORG 10-11	ITA2-R11	11			

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ITU-R Recommendations

NOTE – In every case the latest edition of the Recommendation or Report should be used.

Recommendation ITU-R M.257 – *Sequential Single frequency selective-calling system for use in the maritime mobile service*

Recommendation ITU-R M.476 – *Direct-printing telegraph equipment in the maritime mobile service*

Recommendation ITU-R M.491 – *Translation between an identity number and identities for direct-printing telegraphy in the maritime mobile service*

Recommendation ITU-R M.493 – *Digital selective-calling system for use in the maritime mobile service*

Recommendation ITU-R M.541 – *Operational procedures for the use of digital selective calling equipment in the maritime mobile service*

Recommendation ITU-R M.585 – *Assignment and use of maritime mobile service identities*

Recommendation ITU-R M.625 – *Direct-printing telegraph equipment employing automatic identification in the maritime mobile service*

Recommendation ITU-R M.633 – *Transmission characteristics of a satellite emergency position-indicating radio beacon (satellite EPIRB) system operating through a satellite system in the 406.0-406.1 MHz band*

Recommendation ITU-R SM.1052 – *Automatic identification of radio stations*

Recommendation ITU-R SM.1600 – *Technical identification of digital signals*

Recommendation ITU-R SM.1681 – *Measuring of low-level emissions from space stations at monitoring earth stations using noise reduction techniques*

Recommendation ITU-R SM.2039 – *Spectrum monitoring evolution*

Report ITU-R SM.2304 – *Application of technical identification and analysis of specific digital signals*

ITU-T Recommendation

Recommendation ITU-T E.212 – *The international identification plan for public networks and subscriptions*

5.9 Pulse measurements

5.9.1 Introduction

Pulsed emissions can occur from a variety of sources, including:

– Radar emissions.

– Emissions from digital TDMA systems.

– Emissions from electrical or electronic equipment.

To characterise a pulsed emission, measurement of the same parameters as for other emissions is necessary, which are described in other chapters of this Handbook. These include:

– Average level / field strength.

– Frequency.

– Bandwidth.

This provides specific information on the pulse level measurement and on the measurement of other basic parameters of pulsed emissions.

5.9.2 Basic pulse parameters

The basic parameters of a pulsed emission for which measurements are described in this section are:

– Peak level (A).

– Pulse length (τ).

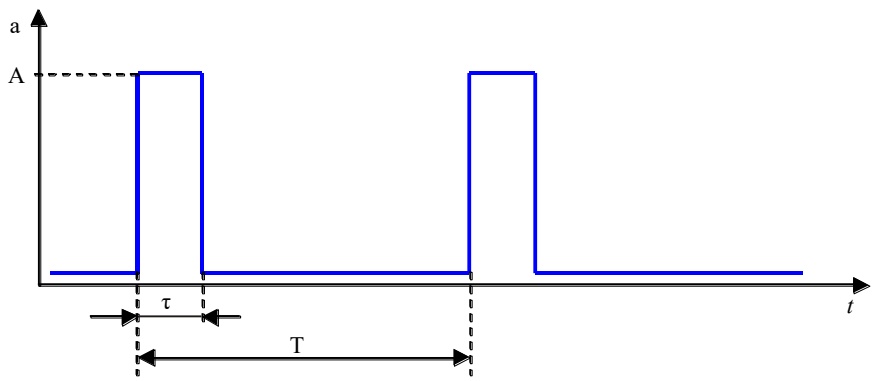
– Pulse period T or pulse repetition frequency (PRF = 1/*T*).

– Pulse rise and fall time (t_r and t_f).

Mathematical pulses are usually described having a rectangular shape in the time domain, like shown in Fig. 5-98.

FIGURE 5-98

Rectangular pulsed signal in the time domain



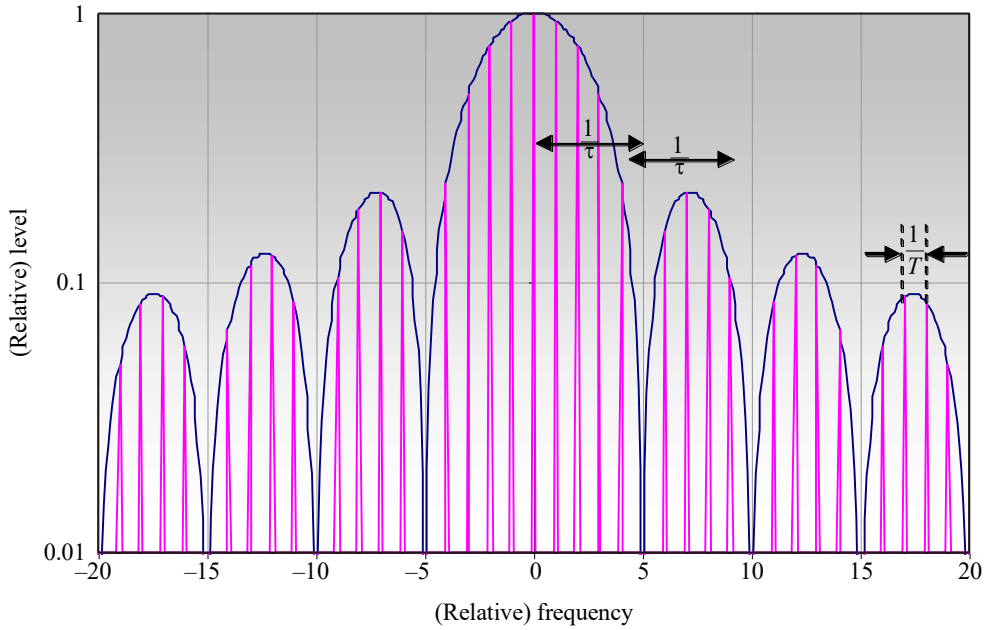
Spectrum-4.9-01

Applying a Fourier Transform to the time signal in Fig. 5-98, a rectangular pulsed signal in the frequency domain looks like in Fig. 5-99.

The actual spectrum consists of distinct spectral lines spaced by $1/T$. The peaks of these spectral lines follow a $\sin(x)/x$ function with minima spaced $1/\tau$. The "main lobe" in the frequency centre has the width of $/\tau$.

FIGURE 5-99

Rectangular pulsed signal in the frequency domain

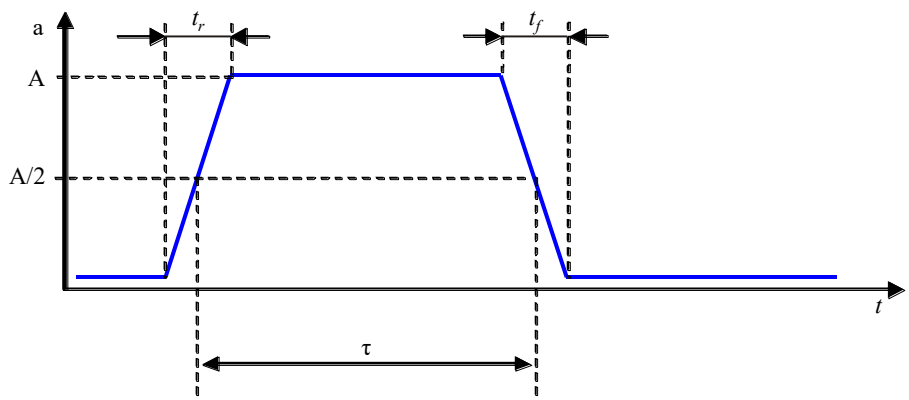


Spectrum-4.9-02

Real-world-pulses require a certain time to arise to their full power, and do not fall back to zero in a sudden instant of time. For that, they have a characteristic shape in time. Taking this into account leads to an idealized shape of a trapezoid as shown in Fig. 5-100.

FIGURE 5-100

Trapezoidal pulse in the time domain



Spectrum-4.9-03

The pulse length is usually defined between the points where the amplitude is half of the peak amplitude.

The rise time t_r and the fall time t_f have influence on the actual spectrum and its width. They are therefore important pulse parameters that may be measured to fully characterise the emission. Since real pulses usually do not have ideal sharp “edges” of the rise and fall slopes, it is necessary to state the level range within which rise and fall times are given. Common values are 10%-90% for rise time, and 90%-10% for the fall time.

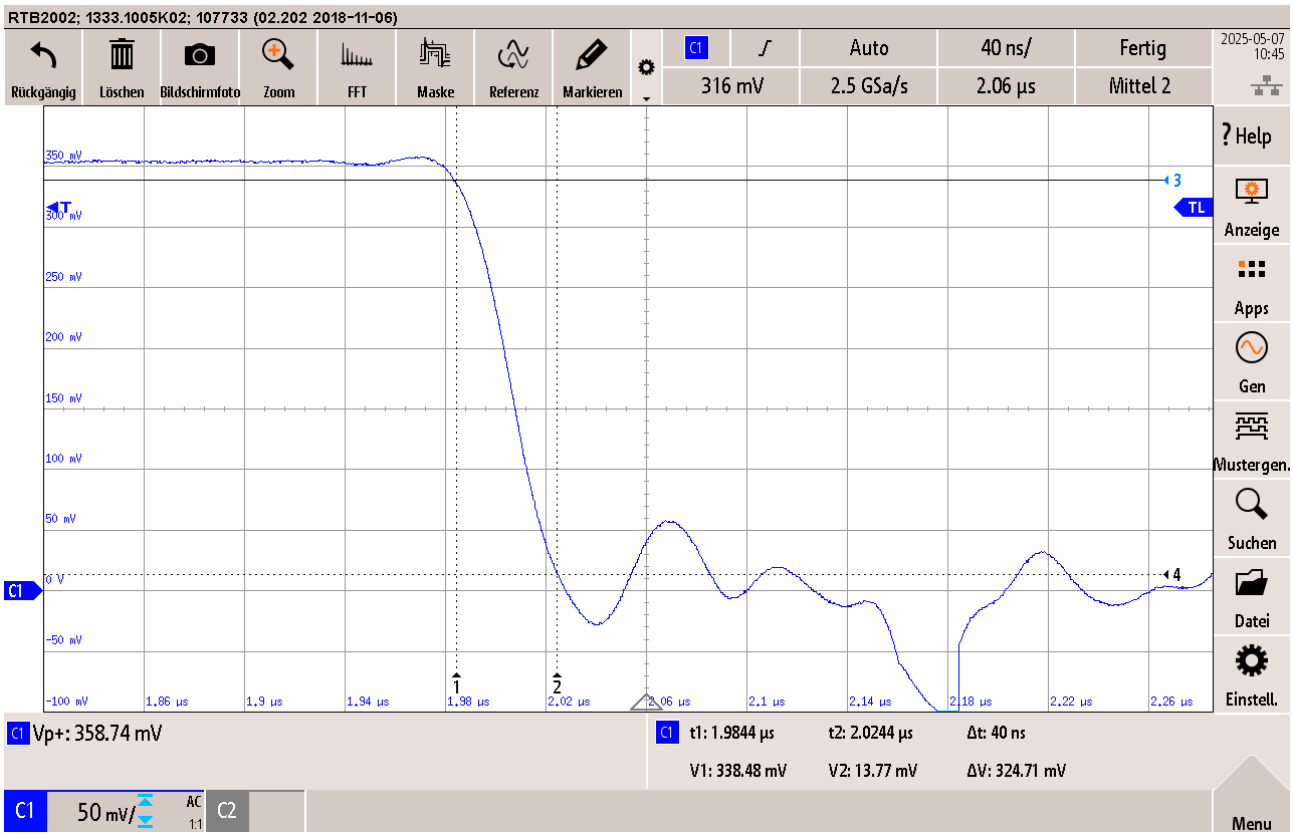
5.9.3 Measurements in the time domain

All pulse parameters mentioned in § 5.9.2 can be measured in the time domain. This is usually done with an oscilloscope connected to the video output of a receiver. It is important that the level of this IF output does not have an automatic gain control and that its bandwidth is sufficient not to influence the timing measurement (see § 5.9.6). Today very fast oscilloscopes are available that may be able to capture and display the RF signal directly.

The fall time of the pulse in Fig. 5-101 is the difference between the two markers, displayed at the bottom as Δ = 236.36 ns. Rise and fall times of most pulsed emissions are very short and measurement of them requires a high bandwidth of the equipment. When this measurement is done off the air, the wanted signal has to be very strong compared to other signals on neighbouring frequencies.

FIGURE 5-101

Pulse fall time measurement with an oscilloscope



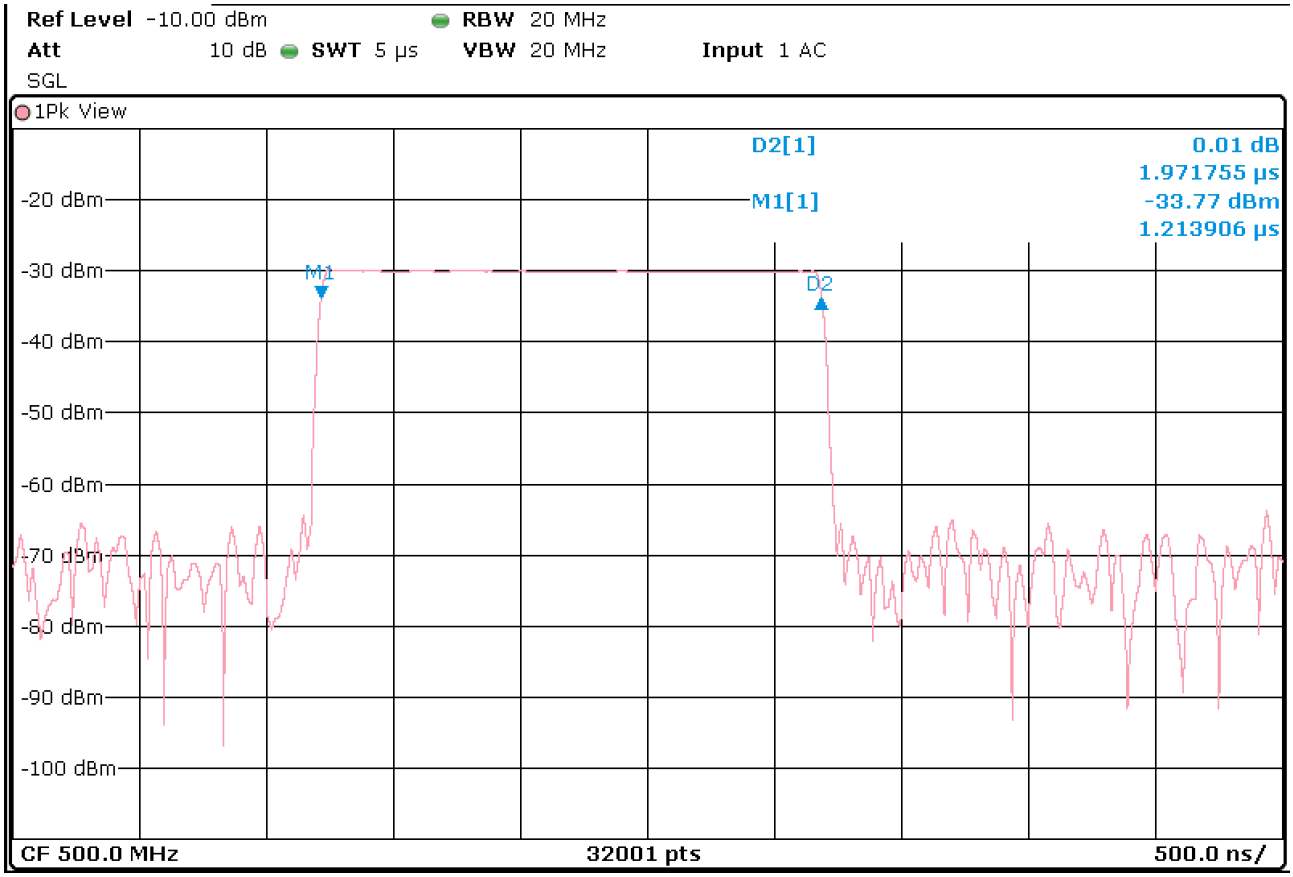
When using an oscilloscope, it must be noted that the level display is usually in linear units, not logarithmic. However, the final display is only linear when the oscilloscope is connected to a linear video output of the receiver or analyser. Many monitoring receivers and spectrum analysers only have a logarithmic video output. In this case the level display of the oscilloscope is also logarithmic. The error introduced due to this fact can be neglected for measurements of the pulse length. However, automatic measurement routines for pulse rise and fall times are not valid in this case. They have to be measured manually instead.

The timing parameters can directly be read from the oscilloscope display.

Modern spectrum analysers often allow very short sweep times in zero span mode which in fact results in a time domain representation of the signal. Together with sufficient resolution bandwidth (RBW), they also allow pulse measurements in the time domain (see Fig. 5-102).

FIGURE 5-102

Pulse length measurement with a spectrum analyser



Note that when measuring the pulse length on a logarithmic level scale, the correct points to set the markers are 3 dB below the peak level.

When measuring pulse timings with a spectrum analyser it is important to use the widest RBW available. Care must be taken not to influence the displayed shape of the pulse by too narrow measurement bandwidths. The necessary bandwidth depends on the pulse timing itself. For details, see § 5.9.6.

The peak level of the pulse is more conveniently measured by using the peak detector of a measurement receiver or spectrum analyser. With a few considerations, however, it may also be measured with the oscilloscope: First the indicated level at the highest point in the curve is noted. While the oscilloscope usually shows the peak-to-peak voltage (U_{pp}), the peak detector of a measurement receiver or spectrum analyser would display the effective power level of this reading (or its equivalent receiver input voltage, u). This can be calculated by multiplying the peak-to-peak reading with $1/\sqrt{2}$. RF levels are usually stated in logarithmic units, so the linear input voltage U has to be converted to a logarithmic voltage level u:

$$u\big(\mathrm{dB}(\mu\mathrm{V})\big) = 20 \cdot \log(U(\mu\mathrm{V})) \tag{5-48}$$

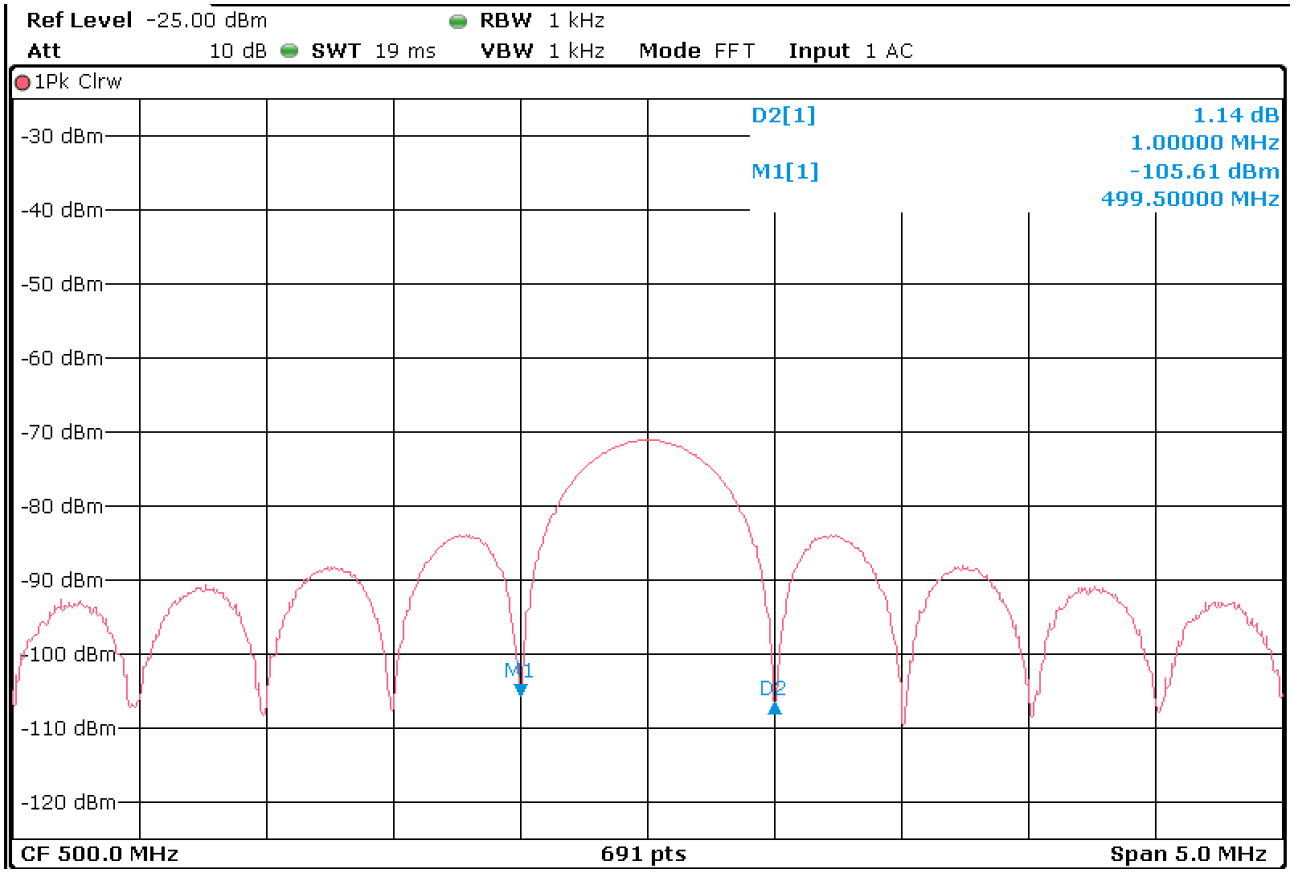
To calculate the RF receiver input voltage of the signal, the amplification of the receiver up to the video output has to be known. The measurement result is reduced by this amplification.

5.9.4 Measurements in the frequency domain

As mentioned earlier, the spectrum of a pulsed emission also allows measurements of some characteristic parameters. However, even with modern spectrum analysers, only the peak level and the pulse length can be measured in the frequency domain. This is because the spectral lines of which the pulse spectrum actually consists cannot be resolved by the analyser. Figure 5-103 shows an example of measurement of the pulse length.

FIGURE 5-103

Pulse length measurement in the frequency domain



The markers in Fig. 5-103 have been placed to the first two minima next to the centre frequency. Their distance (delta) is 1 MHz which is twice the distance between the following minima. The pulse length is therefore 2/1 MHz = 2 µs (see also the text below Fig. 5-98).

To have a good frequency resolution when displaying the true spectrum of the emission, a narrow resolution bandwidth (RBW) in the order of 1/500 of the span is recommended. However, with this setting, no level measurement can be made. To measure the peak pulse level, the RBW has to be at least 1/pulse length.

In any case, frequency domain measurements of pulsed signals with a swept spectrum analyser require the use of the MaxHold function, while FFT based instruments can get the spectrum with one signal record that is long enough to get the pulse repetition rate T.

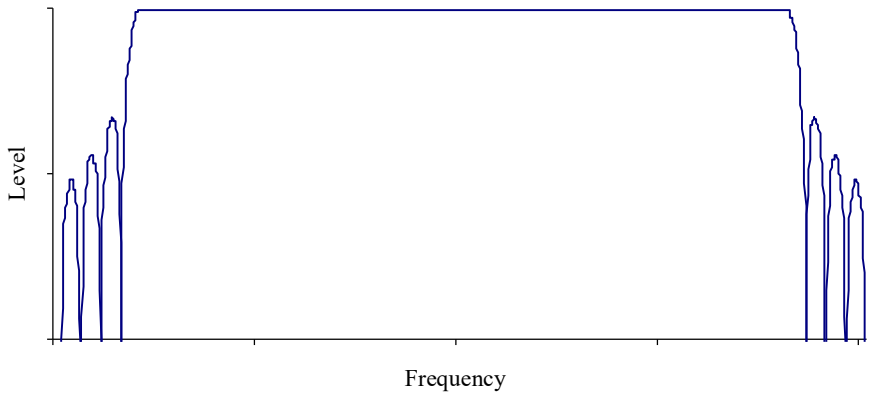
Because the distinct lines of the pulse spectrum correlate in phase, the indicated spectral level increases by 20 dB if the RBW is increased by a factor of 10, whereas the noise floor increases only by 10 dB. Therefore, the maximum signal-to-noise ratio is achieved when the RBW is equal to $1/\tau$. Finding an optimum display of the spectrum is therefore a trade-off between high S/N and good frequency resolution.

5.9.5 Special pulse characteristics

The most common application of pulsed (wanted) emissions is radar. However, apart from simple trapezoidal pulses, some special radar systems also modulate the pulse in amplitude, phase and frequency. These radar emissions have spectra that can be significantly different from the spectrum shown in Figs 5-99 and 5-103. As an example, Fig. 5-104 shows a principle spectrum of a radar that sweeps in frequency during the pulse ("chirp radar").

FIGURE 5-104

Principle MaxHold spectrum of a chirped radar



Spectrum-4.9-07

In case of a chirp radar, its bandwidth and the spectrum shape are predominantly determined by the modulation whereas the residual parts of the spectrum on the left and right having a substantial lower amplitude are mainly determined by the pulse repetition time. The same applies to radars that have digitally modulated pulses.

Some radar systems use alternating pulse lengths and/or PRF. When measuring the spectrum of such a radar, the level minima and maxima may not be as distinct as in Fig. 5-99. As an example, Fig. 5-105 shows the spectrum of a system with two different pulse lengths.

It is obvious that for emissions with alternating pulse lengths, this parameter cannot be measured in the frequency domain. Instead, the time domain measurement has to be done where each pulse can be displayed and measured separately.

5.9.6 Equipment requirements

Apart from standard requirements such as capability to tune the desired frequency, accurately measure the peak level and so on, the bandwidth (or RBW) is most critical when taking pulse measurements. To measure the pulse rise and fall times correctly, the necessary bandwidth of the whole receiving and measurement equipment (receiver, spectrum analyser, video output, oscilloscope) must be high enough to correctly follow the pulse level during these times.

This requirement places high demands even on most modern equipment. With standard receivers and/or spectrum analysers, it may be impossible to measure rise and fall times.

However, the bandwidth of standard equipment is usually high enough to measure level, pulse length and repetition frequency.

Table 5-19 shows the minimum bandwidth requirements for measurements of the different pulse parameters.

FIGURE 5-105

Spectrum of a radar with alternating pulse length

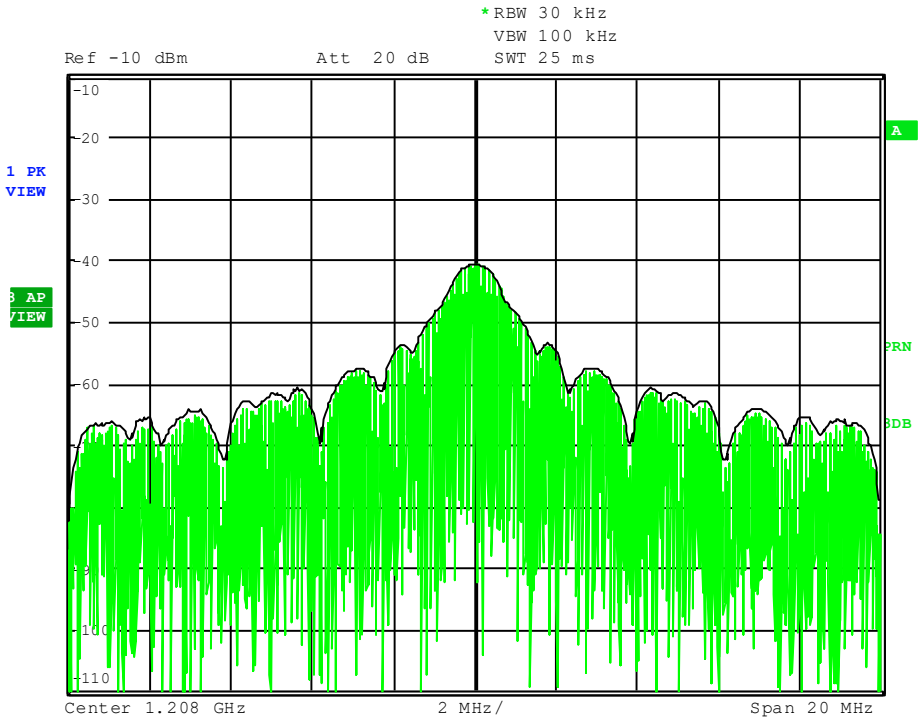


TABLE 5-19

Minimum measurement bandwidth

Measurement of	Minimum bandwidth	Remarks
Spectrum shape, bandwidth, pulse length in frequency domain	– none –	Recommended maximum RBW is 1/100 of span
Peak pulse level	$\frac{1}{\tau}$	For systems with alternating pulse lengths: 1/shortest length
Pulse repetition frequency	$\frac{1}{\tau}$	For systems with alternating pulse lengths: 1/shortest length Measurement accuracy increases at wider bandwidths
Pulse length	$\frac{1}{10\tau}$	Measurement accuracy increases at wider bandwidths
Rise/fall time	$Min(\frac{1}{10t_r};\frac{1}{10t_f})$	Measurement accuracy increases at wider bandwidths

Because of the relatively slow sweep time of sweeping spectrum analysers, combined with very short pulse length and slow PRF of most pulsed signals, the spectrum like in Fig. 5-104 can only be seen after a relatively long time in MaxHold mode. For radar systems, due to slow antenna rotation and low pulse/pause ratios, the necessary observation time may well be many minutes up to hours. With FFT analysers, however, the whole spectrum is already displayed after one single pulse was captured. If the equipment allows continuous capturing for a whole period, the FFT analyser is also capable of measuring the pulse length in the frequency domain for radar systems with alternating pulse lengths. Together with the wide acquisition bandwidth available today, FFT analysers or equipment having full FFT analyser capability are the preferred equipment type for pulse measurements.

5.10 Spectrum occupancy measurements and evaluation

Spectrum occupancy measurements give information to the frequency management about the current use. This information can be on a short time scale, like in preparation for events. On a longer time scale, tendencies on the general usage can be identified.

The measurements can support various frequency monitoring and management tasks such as:

– Channel occupancy registration,

– Frequency band registration,

– Traffic analyses,

– To show that a frequency band is available for new usage after 'refarming',

– Identification of illegal frequency use,

– Interference prevention,

– Long-term analyses.

5.10.1 The term spectrum occupancy

The electromagnetic spectrum can be occupied in two ways:

1 Spectrum is occupied by the administrative issue of a frequency assignment.

2 Spectrum is occupied in a technical sense: a signal can be picked up by an antenna on a certain location.

Both definitions together might lead to the assertion that a certain part of spectrum is actually available. It is important to keep in mind that there are also passive services – and also services that are not necessarily active for most of the times. Vice versa: just because a signal can be picked up, it does not mean that the transmission is licensed.

Naturally, spectrum occupancy here is understood almost exclusively on a technical basis.

The term spectrum occupancy measurements refers to the recording of emission levels during a longer period of time (hours or even days), which is called the duration of monitoring (T_T). The evaluation of these levels above a certain threshold leads to the occupancy during a given period of time (integration times, T_I) and can be presented in a variety of ways.

Occupancy measurements are performed for frequency channels, frequency bands and spectrum resources (see further Report ITU-R SM.2256 and the fundamental paper [SH1977]) such as:

– Frequency channel occupancy measurements (FCO) observe the frequency spectrum of channelized radio applications. Please note that for some services, traffic density on radio channels could result in more informative values than the FCO;

– Frequency band occupancy measurements (FBO) observe the spectrum occupancy at different frequencies for a whole frequency band, regardless of the usual channel spacing;

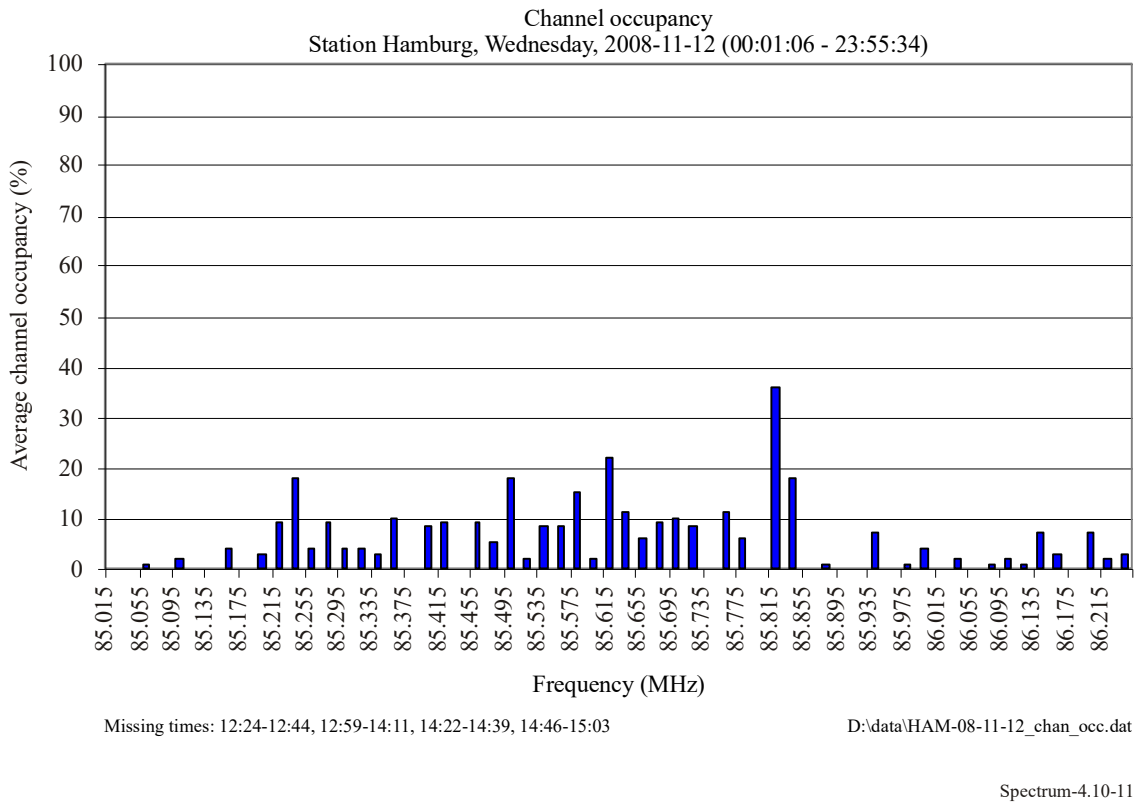
– Spectrum resource occupancy measurements (SRO) investigate the occupancy in terms of the ratio between the number of channels in use to the total number of available channels in a whole frequency band.

This definition is solely based on the level. Questions concerning the source of the emissions and the modulation parameters identification of who, where and when a radio frequency channel or band is occupied are not considered part of spectrum occupancy but rather are discussed in § 5.8 (Signal analysis and transmitter identification).

Figure 5-106 shows an example of an occupancy measurement result.

FIGURE 5-106

Example of a channel occupancy measurement



5.10.2 Measurement considerations and evaluation options

The measurements can be done either manually or automatically or both simultaneously. Automatic measurements can be assisted by manual monitoring if it is necessary to analyse and identify observed emissions, see § 5.8. Manual monitoring can be very time-consuming and only expedient when the required information cannot be registered automatically. More material on computer-aided identification can be found in Report ITU-R SM.2542 and Recommendation ITU-R SM.1600.

In most cases, long-term data or FBO data is not derived by manual means.

The main method of measuring occupancy is the automatic registration technique. To ensure sufficiently accurate evaluations with a suitable level of confidence, the statistical nature of the measurements has to be taken into account when considering the measurement parameters. This is fully explained in Report ITU-R SM.2256 and Recommendation ITU-R SM.1880.

Example: the occupancy for radio signals of an unknown nature has to be recorded, where the occupancy value is divided in intervals of 15 minutes. For this, the channels state should be monitored at least twice per second. If the channel is visited less often (the revisit time T_R is increased), then the occupancy evaluations need integration times T_I that significantly exceed 15 minutes.

Automatic emission monitoring can yield the following information:

Spectrum overview

– This gives general usage information like level (min/max/median/average), spectrograms, etc. It does not comprise the degree of occupancy.

Current channel, frequency band and spectrum resource occupancy

– A measurement that evaluates to the percentage of occupancy over any period. In many cases, this relates to a period of 15 minutes.

Traffic load

– Occupancy data averaged over periods of 60 minutes may be expressed as traffic intensity in Erlang, see Recommendation ITU-R V.665. The time dependent behaviour of the traffic may serve as a basis for the determination of channel requirements and a Quality of Service (QoS) evaluation. Of special significance in this context is the determination of the peak hour. The peak hour and busy hour are specified by the beginning of the relevant measurement interval, e.g. 13:15 and means the occupancy within the measurement interval of e.g. 13:15 – 14:15.

Many emission parameters such as signal strength (minimum, maximum or median value) and the percentage of time that the signal is above a certain threshold level can be evaluated over the whole measurement period or over smaller periods, e.g. 1 hour. The recordable parameters can be determined both by frequency band and frequency channel occupancy measurements and are not bound to specific methods.

As spectrum occupancy analyses can be combined with other data sources, many more additional information can add to the measurement result.

Examples are:

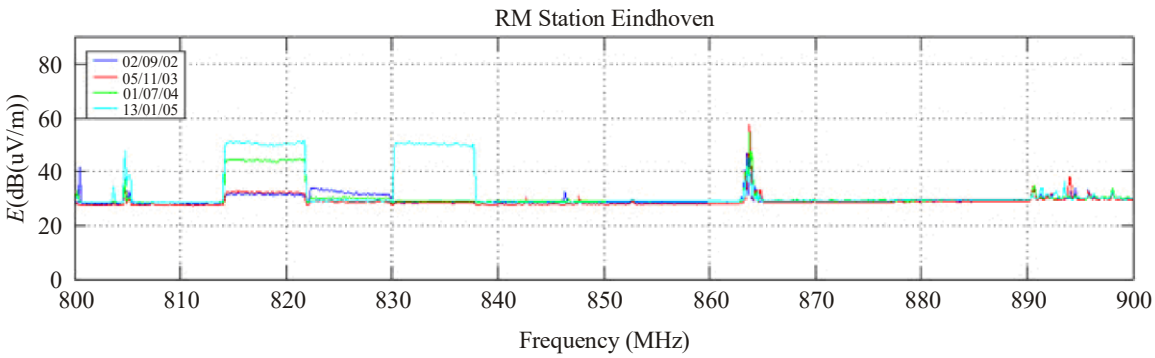
– Determination of the number of users or the spatial distribution of applications, see Report ITU-R SM.2454.

– Usage behaviour expressed as a probability distribution function. This requires a good knowledge of the user behaviour.

– Determination of usage variability or usage stability by correlating the measurement data of identical time bases. This is called Delta monitoring (comparing the results of different measurements of the same frequency band on different dates, by plotting all curves in one plot). An example is shown in Fig. 5-107.

FIGURE 5-107

Example of a Delta Monitoring



Spectrum-4.10-02

5.10.3 Suitable receivers

Measuring receivers (narrow- or broadband) or spectrum are used as receiving equipment. A spectrum analyser or a wideband measuring receiver has the advantage of a higher scanning speed. A monitoring receiver allows individual frequencies to be monitored at random. Requirements specific to occupancy measurements are found in Report ITU-R SM.2256. The specific equipment and measurement settings depend on the signals expected in the frequency band of interest, especially

– the frequency range of interest;

– expected transmission length and bandwidth;

– sensitivity and dynamic range of the receiver;

– suitable high scanning speed;

– adjustable step attenuators as needed;

– sufficient frequency-stability during the measurement time; this may be supported by using an external frequency standard;

– selectivity to prevent the formation of intermodulation products;

– duration of monitoring (T_T);

– measurement site (radio horizon, weather shielding, electricity, computer network access, …)

The measurement uncertainty requirements towards the field strength at the antenna depends on the task. In most cases an input voltage value is sufficient for the detection of occupancy.

Spectrum occupancy analyses are not necessarily limited to registering emissions in the spectrum, but may also applied to data recorded by other instruments, such as protocol analysers.

Also, timing requirements affect the selection of the measurement device. Receivers can be set to any frequency. However, broadband FFT-based systems can acquire a larger bandwidth in far less time. On the downside, the choice of FFT-length determines the frequency resolution, limiting the ability to measure just any arbitrary frequency. This might be especially crucial for channel occupancy measurements.

5.10.4 Site considerations

Various factors should be taken into consideration when selecting a site for occupancy measurements.

In common with most sites used for receiving purposes, the monitoring equipment should be placed at a location that is:

– remote from strong radio transmitters;

– remote from structures and buildings which could cause reflections;

– within the service area of the radio systems to be monitored. Coverage prediction software may be a useful tool to determine the range of reception;

– away from sources of electrical noise, i.e. computers, motors, power installations etc.

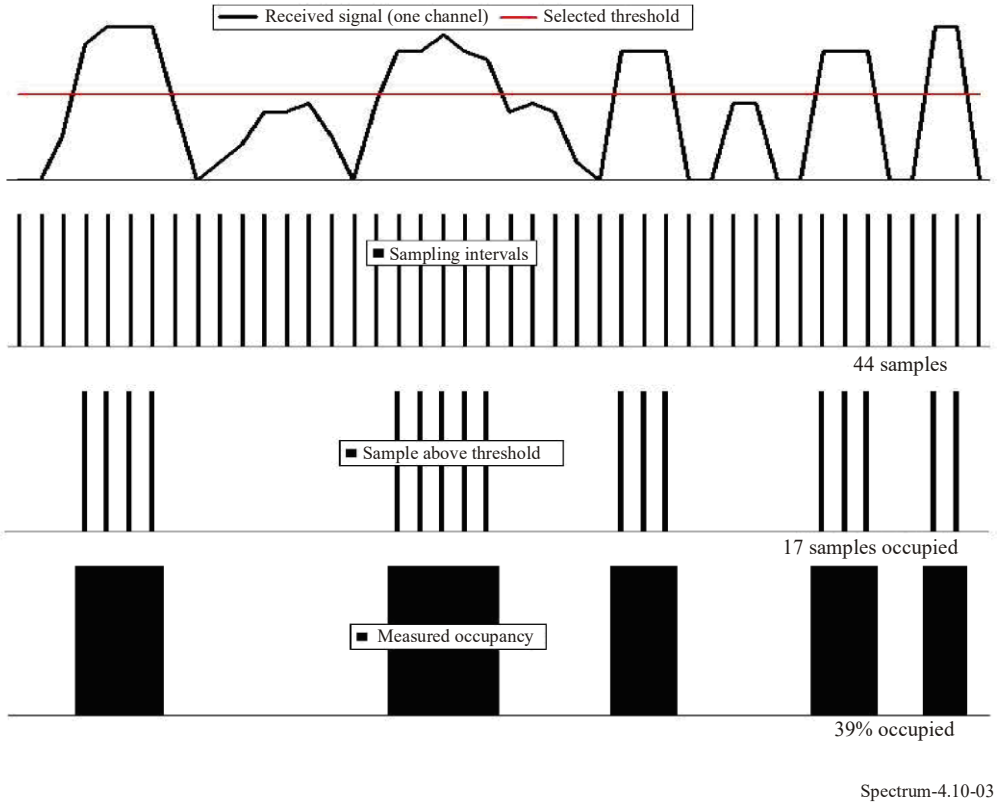
5.10.5 Basic principles and measurement parameters

5.10.5.1 Sampling principles

Figure 5-108 shows the level on a single channel along the time axis. The threshold between the state ‘occupied’ and ‘not occupied’ is set to a fixed level. The sampling instants are shown together with those samples marked as ‘occupied’. In this example 17 of the 44 samples were found to be occupied. Thus, for that channel an occupancy of 39% is recorded. This is summarized into intervals of several minutes or up to 24 hours, as desired.

FIGURE 5-108

Occupancy measurement on a single channel with a typical signal of varying strength



The sample technique usually gives a good estimation of channel occupancy, provided sufficient samples are taken to give a statistically significant result. A guidance on that and the selection of sampling method and timings can be found in Report ITU-R SM.2256 and Recommendation ITU-R SM.1880.

It is important to note that a proper choice of the revisit time T_R is crucial: If the average signal is longer than the revisit time T_R, such signals cannot be missed and are often recorded as a sequence of 'occupied' samples. This leads to the appearance of consecutive samples being dependent. When signal duration is shorter than the revisit time, signals will only be recorded from time to time; the probability of an 'occupied' sample occurring does not depend on whether the preceding sample was 'occupied'; thus, consecutive samples are statistically independent.

Furthermore, sample dependence affects confidence level when evaluating occupancy and must be considered in the planning of measurements; moreover, sample dependence can have different effects on current occupancy measurements at integration times T_I and on overall occupancy measurements for a stationary radio channel.

5.10.5.2 Recording principles

In order to assess the occupancy of as many channels as possible, the proper scanning speed has to be chosen. The monitoring software should therefore be capable of generating the occupancy data for freely selectable time resolutions. In order to obtain comparable results when different measurement systems are used, care has to be taken to ensure a comparable system behaviour.

Example: A scanning receiver is programmed in such a way that 50 samples are recorded every 2 seconds from different radio frequency channels. This means that the system operates with a revisit time of 2 s. The receiver needs time to adjust accurately to the channel. In this example the observation period per channel (sometimes called dwell time, depending on the instrument) is about 5 ms. The observation period per channel depends on the receivers scanning speed.

Even if computer and memory power is tempting, it is not expedient to record raw data since data volumes are too large and difficult to process. It is easier to reduce the data to a specified interval during the measurement.

Depending on the task and the length of the measurement, intervals of 1 minute (1 440 data records per day for a single frequency) may constitute an acceptable compromise between the registration of all data and too high a compression loss. If such a resolution is not necessary (e.g. if the monitoring period takes weeks or month), larger intervals may be adequate. However, the time resolution of the measure equipment should be much higher also in these cases in order to obtain a higher precision when creating moving averages.

5.10.5.3 Threshold setting

The threshold level determines the distinction between and currently occupied or unused frequency. The threshold can be either fixed or dynamic.

A fixed threshold can be defined as the minimum field strength necessary for radio coverage. Care has to be taken in comparing measurements with different thresholds; especially when a dynamic threshold is used.

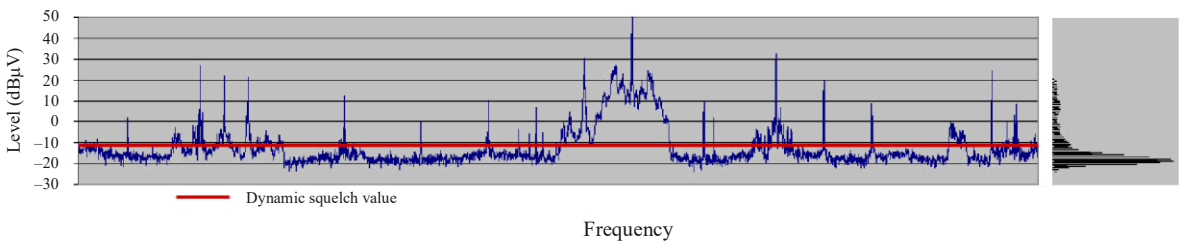
The threshold can be defined by inspecting the noise at the measurement site. A margin of 8 to 12 dB may be added to that figure; 3…5 dB might also suffice in cases where sensitivity is crucial. The selected threshold level for that specific measurement site and setup have to be stored along with the measurement data.

One has to be aware that the background noise level might be different in difference service bands or local areas. As an example, processing results in a broadcasting band will be different from the noise levels in the Aeronautical Service bands.

Where measurements are carried out with a spectrum analyser or receiver, a dynamic squelch can be calculated by various algorithms found in Report ITU-R SM.2256. An example of an approach based on the level-distribution is depicted in Fig. 5-109. The left-hand side of the figure shows the spectrum along with a red threshold line; the level distribution is shown on the right. It can be seen that the threshold is set a few deciBel above the distributions central value.

FIGURE 5-109

Determination of the dynamic squelch



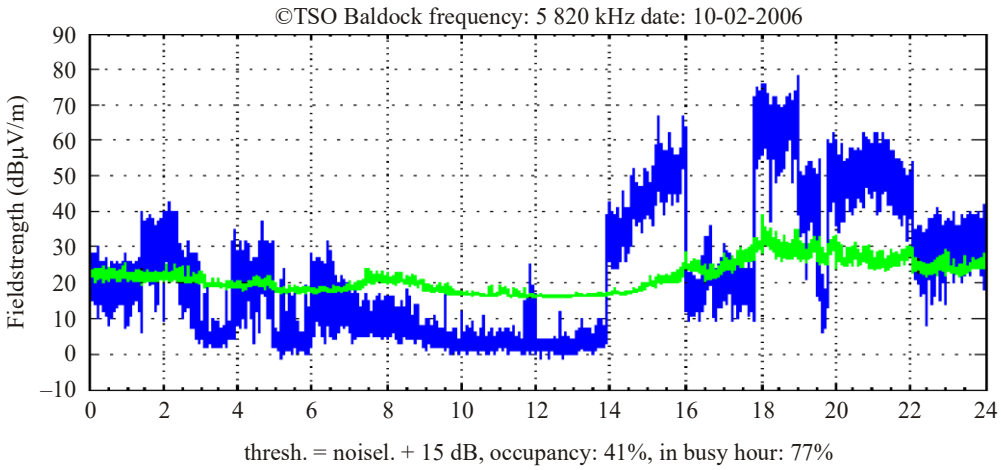
Spectrum-4.10-05

When dynamic thresholds are used, a new threshold can be used for each sweep. This method offers a big advantage in longer measurement cycles. Changes in the noise level or broadband unwanted signals do not falsify the occupancy measurement or render it unusable. However, care must be taken to ensure that the spectra recorded contain an adequate number of noise samples. The noise floor will change slightly over time in VHF/UHF/SHF. However, the change is under normal conditions not more than a few deciBel. Since a number of dB (3 to 5 dB) are added to the noise, this will have no influence. This shows that it is not always needed to calculate a new threshold for every sweep. In case the noise floor is changing more than 5 dB then there are exceptional (propagation) conditions and the results may be corrupted and should not be relied on.

In the HF bands, the situation is completely different. The noise level changes during the day- and nighttime and season with big differences over 24 hours. In that case one should indeed calculate a dynamic threshold versus time. And one should add a few deciBel to the noise level to determine the threshold. In Fig. 5-110 a whole of 15 dB is added to the noise in order to obtain the dynamic threshold level.

FIGURE 5-110

Variation of HF-Noise during one day



Spectrum-4.10-06

A later change of the threshold value is not expedient since this would require raw data to be registered, which would require the storage and handling of large files.

Even if sufficient hard-disk storage space would be available, saving such an amount is problematic and data evaluation difficult. A data reduction during data collection certainly makes sense for various reasons but does imply that the parameters to be set must be known before the measurement is begun. Further discussion of data organization can be found § 5.10.8.

5.10.5.4 Statistical confidence in occupancy measurements

The means of ensuring statistical confidence in occupancy measurements varies according to whether the statistical properties of the channel remain unchanged along the time axis (channel is considered stationary) or change dynamically (channel is considered non-stationary).

Stationary case

If the channel properties are presumed to remain unchanged for long periods of time, the purpose of the occupancy measurements is to assess the probability of spectrum occupancy in such a way that the channel will be in an 'occupied' state at an arbitrary point in time. The overall occupancy value refers only to the channel (or frequency band or resource) and has no specific time reference. Such an assessment requires prolonged measurements. Data collection may take many hours, although data may be accumulated piecemeal during different occasions, e.g. in 15-minute segments of time. The spectrum occupancy calculation result $SOCR_r$ (required for equation 5-49)) is given by the number of detected 'occupied'-states over the number of total attempts to detect the state.

Non-stationary case

If the channel is considered non-stationary, the purpose of the occupancy measurements is to monitor the change in occupancy along the time axis. The spectrum occupancy calculation result $SOCR_r$ (required for equation (5-49)) is given by the number of detected state-changes over the number of total attempts to detect the state change.

Case-dependent determination of occupancy rate

If the hardware capabilities of the radio monitoring instrument allow, occupancy measurements for both stationary and non-stationary channels should be performed at 15-minute integration times T_I. Then, an average is taken using the current spectrum occupancy calculation results $SOCR_r$ in order to generate the overall estimate of probability of stationary radio channel being in an occupied state.

$$SOCR = \frac{1}{R}\sum_{r=1}^{R} SOCR_r \qquad (5\text{-}49)$$

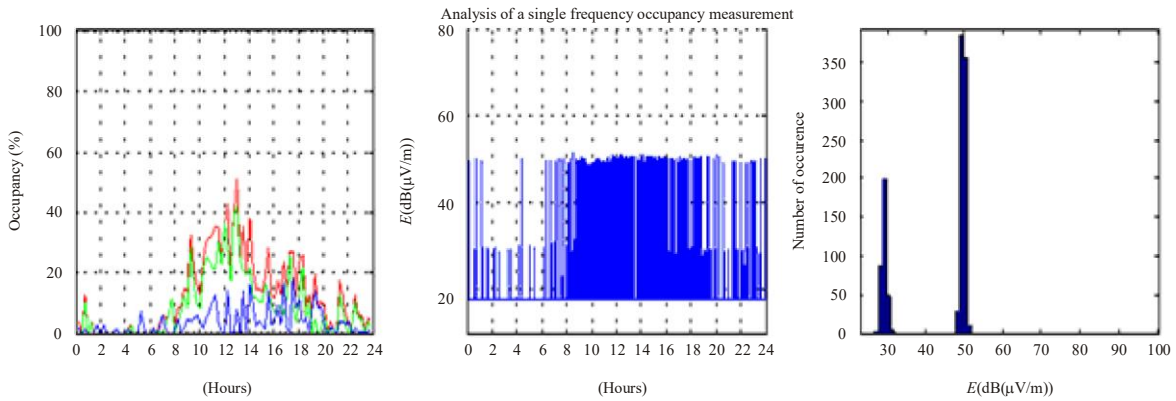
If the radio monitoring equipment is not sufficiently sophisticated to generate accurate occupancy evaluations with suitable confidence levels for 15-minute integration times T_I, a larger T_I value may be used. Alternatively, occupancy estimates may be performed for a single monitoring period lasting multiple hours if the channel can be considered stationary.

5.10.5.5 Limitations and possible solutions

Although accurate occupancy results are expected, it is wise to bear in mind the limitations associated with automatic occupancy monitoring and areas where inaccuracies could occur. Simple automatic monitoring is not able to discriminate between signals received from different stations. It also can not differentiate if mobile users are active outside of the area covered by the measurement setup, which might lead to an underestimation of the traffic by the network during that specific time. Advanced automatic monitoring is able to discriminate between signals from different stations. The occupancy caused by the different stations working on the same channel could be both shown together in an occupancy plot as shown in Fig. 5-111.

FIGURE 5-111

Example of spectrum occupancy from two transmitters sharing a single channel



Spectrum-4.10-04

Most automatic occupancy monitoring systems use a threshold level to establish when a frequency is occupied.

Although the obvious intention is to record the activity of wanted signals, simple automatic monitoring is not able to discriminate between wanted and unwanted emissions. Both types of emission are treated as legitimate channel occupancy.

Undesired signals could originate from any of the following sources:

– unauthorised transmissions;
– strong adjacent channel users;
– spurious and out-of-band emissions from transmitters;
– man-made noise (e.g. electric engines);
– irregular propagation, e.g. due to weather or environmental conditions;
– co-channel users from a distant location.

Care must be taken in system design to remove receiver intermodulation products during the evaluation or avoid them at all. One might be tempted to take account for intermodulation products by automatically inserting an RF-attenuation on alternate scans and then automatically remove all recorded signals which are attenuated by a larger value as compared to the previous recording. However, this measurement technique halves the recording time. It is even not very reliable since emissions might change between the two sweeps.

As a consequence, one has to observe the measurement for a while after starting the process in order to adapt to different situations on the measurement site. Depending on the measurement's total runtime and network availability, a scheduled remote check can help to detect problems. Also, automatic removal or flagging of suspicious records (overload, unexpected bursts in noise level, etc.) can help to improve the overall quality.

5.10.5.6 Specialized scan methods

Sometimes side-effects and tricks can be used to gain additional benefits that are beyond the scope of the relevant Recommendations and Reports.

5.10.5.6.1 Slow channel scanning

This method scans the frequencies at a very much slower rate (as compared to FCO), perhaps only 2 frequencies/s. This method can be used when the identity of the user is transmitted throughout the entire length of the user's transmission and can therefore be obtained by sampling at any time.

This is possible for radio systems like continuous tone-coded squelch system (CTCSS) or digitally coded squelch (DCS).

If a more differentiated statement about the frequency uses is required, it is usually necessary to record and evaluate additional protocol data using dedicated analysers.

5.10.5.6.2 Static channel monitoring

This enables the collection of information about transmission length and can also be used in systems where the end user only sends its identification once per transmission. It is not possible to employ scanning techniques because the receiver must remain on a single frequency in order not to miss any information (see Fig. 5-112).

This is applicable for the following types of system:

– 5-tone Selective Calling (SELCAL).

– Automatic Transmitter Identification System (ATIS).

– MPT 1327 trunking control channel.

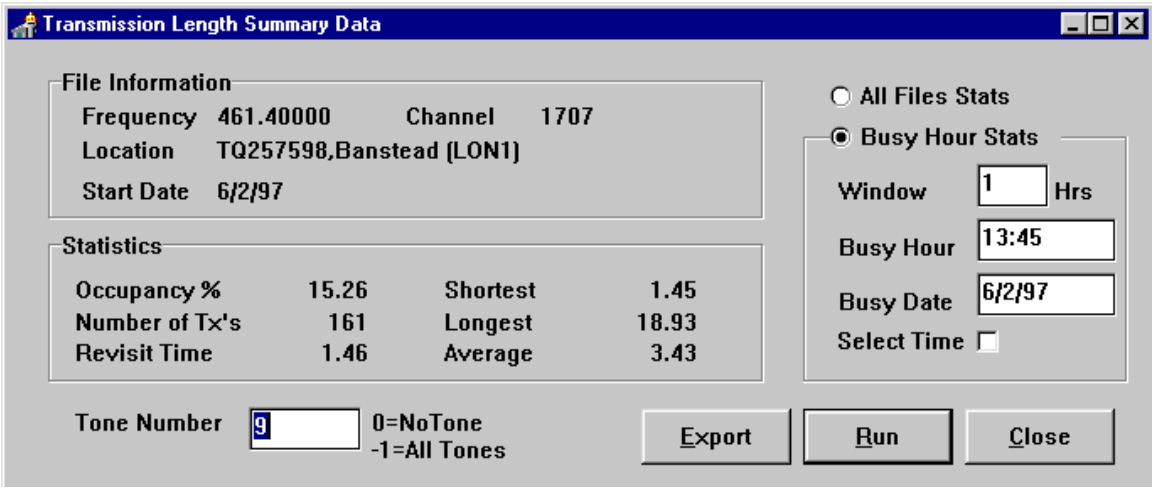
– POCSAG paging.

If additional information on individual users is obtained, it is then possible to sub-divide the total occupancy for that frequency into specific occupancy values for each user.

In the case of applications controlling traffic flow over control channels, e.g. as in trunked radio, or which can be reduced to a single channel (e.g. DSC, POCSAG) it is possible to derive a very accurate traffic analysis from the recorded protocol data.

FIGURE 5-112

Example of static channel monitoring



Spectrum-4.10-07

5.10.6 Notes on frequency ranges

The basic principles shown in Recommendation ITU-R SM 1880 for occupancy measurements apply below and above 30 MHz. In past times, frequency channel occupancy (FCO) measurements were not used in the frequency band below 30 MHz. However, with the increasing demand for spectrum resources, the growing complexity of spectrum management and the high availability of FFT-based measuring instruments, FCO measurements are becoming increasingly important even in the radio spectrum's lower portion. Please note the frequency range dependent considerations on the threshold settings found in § 5.10.5.3.

5.10.6.1 Frequencies below 30 MHz

For occupancy monitoring below 30 MHz, the analysis unit must provide a selection of analysis filters with bandwidths in the range of about 100 Hz up to 10 kHz. Frequency measurements with accuracy of approximately 1 Hz assist by helping to identify signals. The measurements usually need longer observation times, e.g. due to the propagation conditions (only at night, only in the afternoon, …)

5.10.6.2 Frequencies above 30 MHz

Spectrum occupancy measurements are far more common above 30 MHz. Listed below is a selection of different uses of occupancy measurements.

5.10.7 Storage, presentation and analysis of collected data

When occupancy data has been collected there is a requirement to analyse the results and present them in a useful format. Data needs to be turned into information and ultimately knowledge.

Spectrum occupancy data storage and management could be implemented using a multi-tiered and integrated approach. A time-series database (such as InfluxDB) could be used as the core for storing high-precision measurement data, in order to leverage its optimization for timestamp-based information. A relational database (such as PostgreSQL) could be used to manage metadata and configuration details, in order to manage the structured data and the data easily to be queried. To express the complex relationships between data, a knowledge graph could be constructed using a graph database (such as Neo4j). Large-scale raw data could be stored in distributed file systems (e.g. HDFS) or cloud-based data lakes, in order to facilitate subsequent in-depth data analysis. More on the topic of data-lifecycle and data keeping can be found in Chapter 4.

The monitoring system may already have presentational and analytical functions built into the software supplied. Irrespective of whether these functions are included within the measurement gathering software, or supplied as a separate application, the processes are similar.

The complete process is described in three steps:

1 Measuring and collecting data.

2 Processing and converting data into information (tables, plots, graphs, maps etc.).

3 Presenting the result for written reports or display on websites, etc.

Depending on the number of use cases and requirements, computer-based interactive exploration and display methods can lead to flexible ways of reporting the measurement results to the frequency management or other interested parties. Nonetheless, the basic workflow is as outlined above.

5.10.8 Exchange of data

The measurement results might be interesting for different parties. That might be case e.g. for neighbouring administrations that want to coordinate frequency assignments along country borders. In such cases it is important to use a unique and unambiguous format that allows correct interpretation of the data the cooperating parties deliver to each other over agreed communication channels. One possibility is given in Recommendation ITU-R SM.1809. Another possibility to exchange or even to publish data is to use the various options given by the world-wide web, like hypertext mark-up language (HTML), extensible markup language (XML) or Javascript object notation (JSON).

As a further example, Recommendation ECC/REC/(05)01 [ECC0501] describes a comma separated value (CSV) file format for this that purpose.

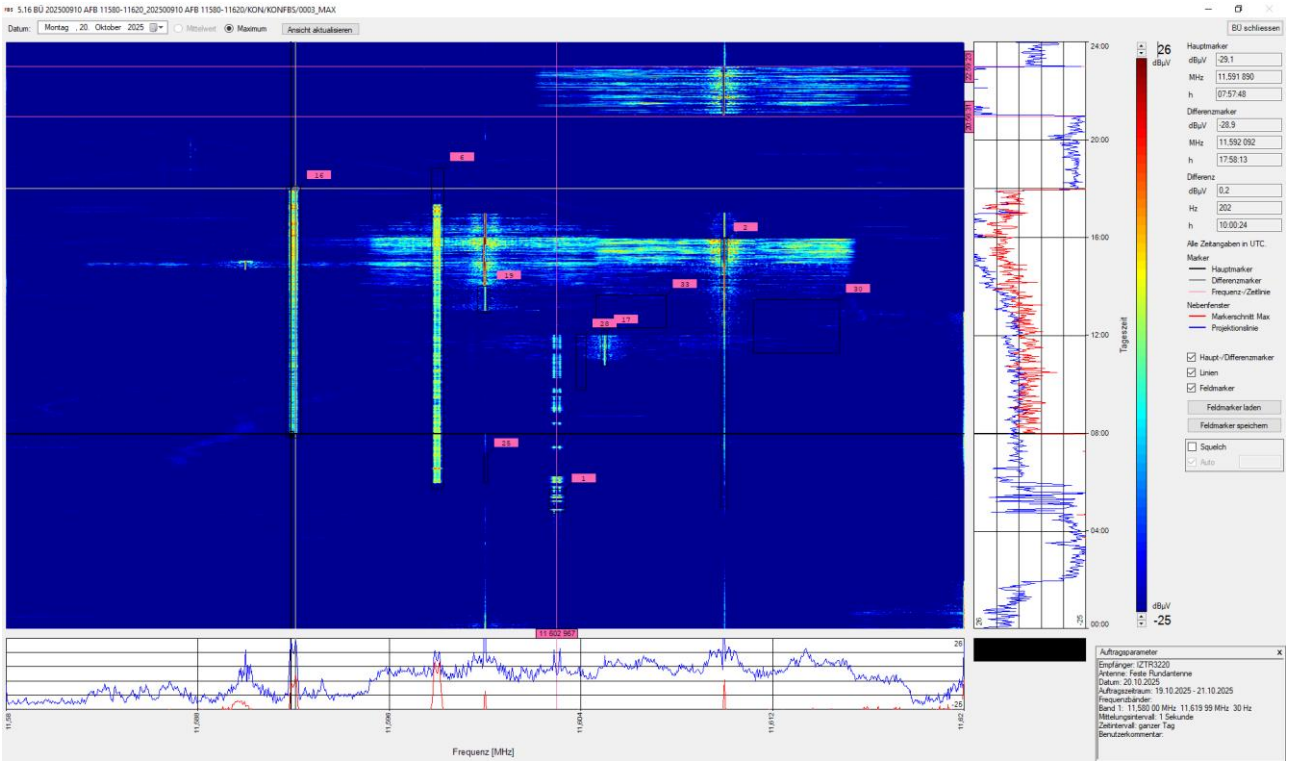
5.10.9 Examples

Some examples of various occupancy measurements are presented below.

Figure 5-113 shows a spectrogram and the accompanying spectra as well as a display of the total level in the measured frequency range during the record time. These data collections serve as the base for further evaluations. The possibility to add manual markers and remarks on top of the automatic generated plots is a handy feature.

FIGURE 5-113

Example of a frequency band measurement



Colorized tabulated data can help identifying usage patterns and preferences as shown in Fig. 5-114.

FIGURE 5-114

Example of a quick overview of channel occupancy measurements

Short overview
Channel occupancy over time

Hours	0..1	1..2	2..3	3..4	4..5	5..6	6..7	7..8	8..9	9..10	10..11	11..12	12..13	13..14	14..15	15..16	16..17	17..18	18..19	19..20	20..21	21..22	22..23	23..24
Channel 01	15%	16%	17%	18%	19%	21%	22%	24%	25%	27%	29%	31%	33%	36%	38%	41%	44%	47%	61%	27%	23%	21%	18%	19%
Channel 02	8%	9%	8%	5%	9%	9%	19%	5%	13%	12%	4%	12%	14%	5%	6%	19%	38%	24%	16%	18%	5%	25%	11%	7%
Channel 03	10%	11%	12%	17%	17%	18%	2%	5%	17%	25%	14%	22%	12%	24%	18%	24%	21%	4%	12%	1%	2%	15%	25%	10%
Channel 04	4%	10%	10%	13%	5%	15%	6%	2%	9%	6%	11%	1%	11%	26%	34%	10%	41%	7%	7%	24%	6%	26%	23%	11%
Channel 05	14%	12%	5%	4%	5%	5%	18%	4%	16%	1%	4%	12%	27%	15%	8%	9%	27%	2%	4%	24%	17%	30%	24%	19%
Channel 06	9%	9%	9%	1%	3%	1%	6%	7%	13%	11%	14%	8%	27%	26%	8%	12%	25%	39%	35%	11%	28%	17%	10%	8%
Channel 07	10%	1%	1%	8%	6%	2%	7%	14%	15%	2%	25%	16%	34%	10%	15%	21%	46%	26%	21%	8%	15%	33%	21%	12%
Channel 08	4%	15%	8%	15%	1%	3%	15%	11%	2%	19%	27%	21%	10%	30%	32%	9%	30%	9%	50%	9%	23%	21%	22%	23%
Channel 09	4%	14%	2%	5%	17%	2%	2%	20%	1%	8%	9%	23%	24%	10%	9%	12%	15%	3%	7%	23%	22%	4%	4%	35%
Channel 10	0%	8%	16%	15%	5%	11%	4%	19%	7%	15%	17%	15%	14%	20%	24%	37%	38%	44%	7%	19%	25%	7%	31%	16%
Channel 11	12%	1%	15%	16%	1%	1%	6%	9%	22%	20%	12%	24%	12%	32%	18%	14%	5%	11%	9%	15%	14%	19%	32%	12%
Channel 12	10%	13%	13%	3%	4%	9%	1%	3%	6%	27%	18%	21%	3%	2%	36%	5%	37%	11%	20%	23%	15%	9%	29%	16%
Channel 13	8%	2%	1%	12%	17%	10%	8%	16%	24%	26%	16%	25%	24%	24%	6%	37%	14%	20%	6%	9%	24%	24%	30%	20%
Channel 14	13%	8%	1%	8%	4%	3%	7%	14%	25%	10%	26%	24%	8%	23%	20%	2%	30%	46%	22%	24%	17%	3%	23%	22%
Channel 15	2%	14%	0%	15%	10%	19%	15%	16%	24%	27%	18%	19%	20%	30%	37%	8%	43%	29%	37%	20%	28%	20%	31%	1%
Channel 16	3%	12%	11%	4%	2%	17%	8%	7%	15%	12%	26%	11%	19%	17%	17%	30%	34%	20%	49%	8%	6%	7%	3%	5%
Channel 17	14%	0%	4%	1%	8%	3%	7%	7%	23%	7%	13%	7%	24%	4%	3%	9%	2%	14%	8%	23%	5%	15%	28%	10%
Channel 18	10%	3%	1%	10%	17%	16%	12%	12%	17%	25%	23%	24%	28%	4%	35%	37%	18%	10%	12%	10%	18%	25%	33%	25%
Channel 19	3%	7%	15%	13%	7%	10%	16%	6%	1%	5%	13%	7%	27%	22%	13%	23%	39%	11%	21%	10%	26%	4%	28%	4%
Channel 20	3%	1%	6%	2%	12%	14%	1%	12%	1%	23%	2%	23%	4%	17%	19%	20%	13%	18%	12%	3%	28%	14%	11%	9%

< 10% 10% <-> 20% > 20%

Spectrum-4.10-12

The next example in Fig. 5-115 shows data of a system that only indicates that a signal observed was above the pre-set threshold level. The data is presented in segments of 24 hours, where the level data is evaluated in blocks of 15 minutes.

FIGURE 5-115

Report of occupancy on a single channel

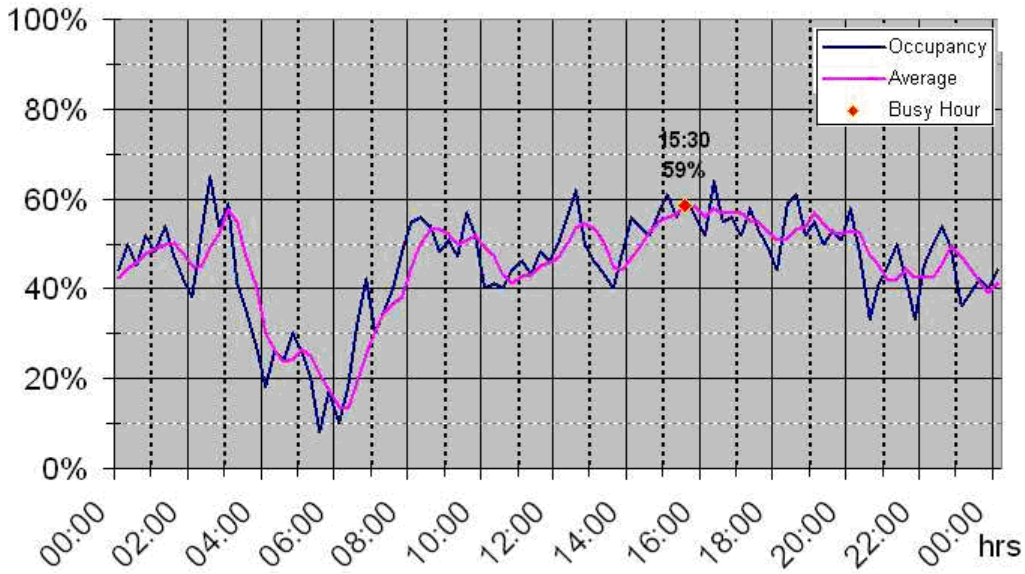
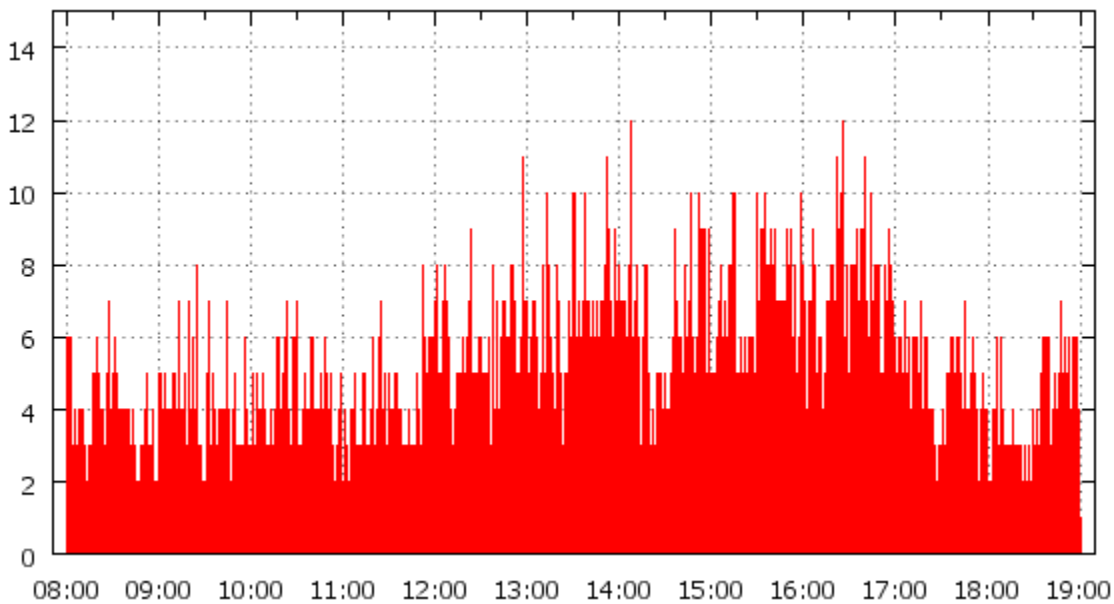


Figure 5-116 shows an extended FCO analyses that tries to answer how many channels of a network are active in parallel.

FIGURE 5-116

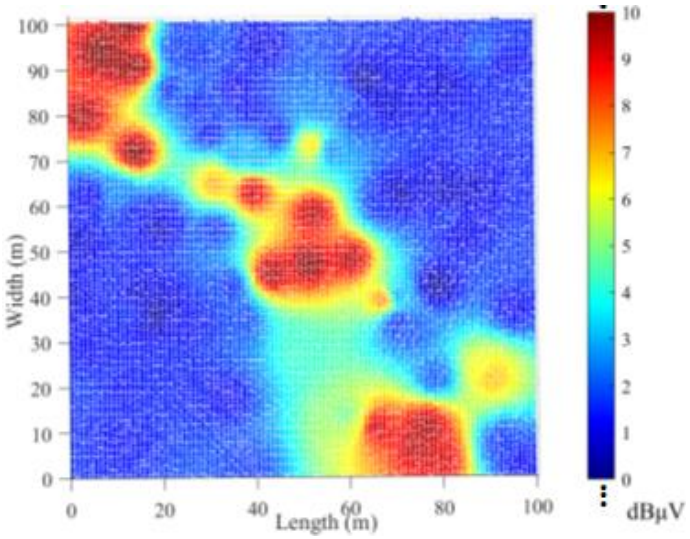
Number of parallel occupied channels



The idea of spectrum occupancy is not limited to a single location. It can also be extended over a certain geographical area. Figure 5-117 is such an example. It shows the level distribution on a certain frequency in an area. This is turn can be translated to an occupancy map. Such a map is conceptually different to a coverage map – which is bound to an agreed coverage criterion.

FIGURE 5-117

A visualization example of radio map in Nanjing, frequency: 106 MHz



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European Conference of Postal and Telecommunications Administrations (CEPT) [ECC0501] *ECC Recommendation (05)01: Harmonisation of automatic measuring methods and data transfer for frequency band registrations*

KOZMIN V. A., PAVLYUK A. P., TOKAREV A. B. [KPT2014], *Accuracy requirements for a radio-frequency spectrum occupancy evaluation*. Eletrosviaz, No. 6. (in Russian – the article translated into English is available at: http://www.ircos.ru/en/articles.html).

TOKAREV A. B., KOZMIN V. A., PAVLYUK A. P., POLEV V. Y. [TKPP2024], *Duration of data collection when measuring occupancy of stationary radio channels // Systems of Control, Communication and Security*, No. 1. https://sccs.intelgr.com/arch.html (in Russian – the article translated into English is available at: http://www.ircos.ru/en/articles.html).

ITU-R Recommendations

NOTE – In every case the latest edition of the Recommendation is encouraged to be used.

Recommendation ITU-R SM.1880 – *Spectrum occupancy measurements and evaluation*

Recommendation ITU-R SM.182* – *Automatic monitoring of occupancy of the radio-frequency spectrum*

Recommendation ITU-R SM.1536* – *Frequency channel occupancy measurements*

Recommendation ITU-R SM.1600 – *Technical identification of signals*

Recommendation ITU-R SM.1753 – *Method for measurements of radio noise*

Recommendation ITU-R SM.1793* – *Measuring frequency channel occupancy using the technique used for frequency band measurement*

Recommendation ITU-R SM.1809 – *Standard data exchange format for frequency band registrations and measurements at monitoring stations*

**Note by the Secretariat*: This Recommendation has been suppressed and replaced by Recommendation ITU-R SM.1880 – Spectrum occupancy measurements.

ITU-R Reports

NOTE – In every case the latest edition of the Report is encouraged to be used.

Report ITU-R SM.2154 – *Short-range radiocommunication devices spectrum occupancy measurement techniques*

Report ITU-R SM.2256 – *Spectrum occupancy measurements and evaluation*

Report ITU-R SM.2405 – *Spectrum management principles, challenges and issues related to dynamic access to frequency bands by means of radio systems employing cognitive capabilities*

Report ITU-R SM.2542 – *Next generation spectrum monitoring – proactive, autonomous and data-driven*

ITU-R Handbooks

NOTE – In every case the latest edition of the Handbook is encouraged to be used.
Handbook on Computer-Aided Techniques for Spectrum Management (CAT)

5.11 Coverage measurements

5.11.1 Introduction

Coverage measurements try to assess if a certain radio service or radio application is usable at a certain level of quality on a certain spot. This spot can be a single location, a certain area or even the whole of a nation.

In analogue modulated systems it may be sufficient to measure the field strength. Due to certain circumstances and principles inherent to the reception of digitally modulated systems, the coverage of digital terrestrial networks needs to be measured differently from analogue networks.

This text describes the measurement principles, procedures and necessary equipment focused on mobile coverage measurements of radio transmitters and networks. Based on that, specific measurement systems and proceedings need to be tailored to the individual radio system and measurement demands. More information regarding specific measurements on specific radio services can be found in Chapter 5 of this Handbook.

The ITU terms and definitions database (http://www.itu.int/ITU-R/go/terminology-database), which should be used as recommended in the most recent version in force of Recommendation ITU-R V.573, defines a 'coverage area (of a terrestrial transmitting station)' to be an "area associated with a transmitting station for a given service and a specified frequency within which, under specified technical conditions, radiocommunications may be established with one or several receiving stations.", and refers for further details to Recommendation ITU-R V.573-4.

The level of service quality depends on requirements of the service and on conditions given by demands on that service. The demands may be set by the frequency assignment conditions or other criteria such as recommendations, standards or agreements between the administration and service provider. This distinction separates the technical ability of a radio receiver that is able to access that service somehow and somewhere ('technical coverage') from a defined reception scenario ('administrative coverage'). Nonetheless, technical decisions regarding how to do the measurements often get quite complex to explain. If measurement engineers have certain degrees of freedom, parameters that lean closely to the users experience with the radio service of interest will be easier to accept.

Monitoring services have to measure the coverage of radio services and networks for different purposes:

– To verify predictions of computerised tools used for the planning of the network.

– To verify compliance with license conditions if part of the license is that a certain area, percentage of an area or percentage of the population is covered by the radio service.

– To verify the quality of service in a given area.

– To assess the receiving conditions at certain locations where interference is reported.

The measurement purposes determine the measurement setup, along with the design of the overall measurement campaign. For interference cases, in situ measurements at a single location suffice in most cases, whereas nationwide coverage measurement campaigns require much more effort and preparatory planning.

5.11.2 Ways of taking measurements

Coverage measurements can be conducted in many ways, according to the desired results, radio service and reception scenario. Common ways include:

– Recording of electric and/or magnetic field strength levels with calibrated measurement equipment; comparison with reference values

– Passive measurements with dedicated equipment: recording of service-dependent receiver output values such as number of dropped audio frames, received signal strength indicator

– Active measurements with dedicated equipment: recording of service-dependent receiver output values such as data throughput rates, ability to perform outbound voice calls, voice call quality by active use of the network

– Crowd-sourcing: network users send usage reports to dedicated servers. The reports contain information about e.g. the network identification, location, time, signal strength. The reception scenario is "as is" – no reliable knowledge can be gained about the true reception conditions, as well as the receiving device. This type of data collection is popular in public land mobile networks and can give hints towards future measurement locations. In most cases, a direct comparison with data derived from well-defined measurement processes is not possible.

While the first three types are embedded within a defined reception scenario, along with comparison to standardized or agreed values, crowd-sourcing results are an indicator of the overall's network state in regards of the user's experience – provided a high number of users contribute to the data collection. The type of used transceivers is out of any control, as well as the reception scenario. Nonetheless, if reports exist for a spot by different users on different days, one can assume that the average results provide a statistically relevant representation of the network's state. For example: in housing areas, reports can be gathered in many different scenarios (cellar, attic, garden, at the window or deep indoor). In contrast, reports taken on motorways can be deemed quite typical.

5.11.3 Basic considerations

As with any other measurement, the workflow consists of the following steps:

(1) Information gathering;

(2) Planning and design of measurement setup and organization;

(3) Execution phase;

(4) Data evaluation and reporting.

Some general considerations are given in the following subsections.

5.11.3.1 Information gathering

This step covers theoretical preparatory work. It has to be clarified what service is to be investigated and to be decided which parameters have to be obtained – either as direct observable or by indirect means (i.e. what field strength is associated with a certain service quality level). Those requirements can often be found within coverage obligations (i.e. 'x% of the population or nation have to be covered with quasi error-free reception', …), while specific definitions on observable values can be found in documents like Recommendation ITU-R SM.1447 or ETSI TS 102 658, just to name a few.

From that point on, it has to be decided about the measurement conditions, namely antenna parameters (gain, pattern, height) and the nature of the observable quantity at the user receiver's input (e.g. field strength) and the receiver's output (e.g. successful decoding of network information).

Dependent on the service, the target location and reception scenario, it has to be decided on the measurement platform (vehicles with antenna mast for stationary reception; vehicles recording while moving; backpack systems for pedestrian or indoor data gathering).

Based on the knowledge so far, predicted coverage data can give hints in regards of the measurement routes. This information is usually provided by the network operator, the demands of the administrations of potential network users. A common approach is to commute back and forth on the edge of the predicted coverage area,

revealing the planning parameter's accuracy. Nonetheless, examination of a certain area inside of the predicted coverage area is also valid to estimate the number of households that can be regarded as being covered (see Report ITU-R SM.2504). While Recommendations ITU-T E.800-E.809 offer lots of information regarding terms and definitions related to the quality of telecommunication services, Recommendation ITU-T E.806 is especially noteworthy due to its generic guide regarding the size and selection of measurement areas to get statistical relevant results.

Beyond that, the required data processing out of the measurement system, reporting and exchange of data has to be agreed. Detailed data can often be assisted by naming a few aggregate values that describe the results of the investigated area which are often termed as 'key performance indicators' (short: KPI). More potential parameters can be found in the BEREC guidelines, see [BEREC2020].

5.11.3.2 Planning and design of measurement setup

The measurement setup is determined by the demands defined in the section above. An exemplary setup for the most common type – car-based measurements – is basically comprised of devices like:

– Radionavigation Satellite Service (RNSS) receivers for position recording (maybe with dead reckoning feature), see § 5.4.3.2.5 and § 7.1;

– Measurement antenna(s);

– Computers to control the measurement devices and record the data;

– Computers to indicate and visualize the driven track on digital maps;

– Distance measuring equipment, if the field strength has to be sampled according to § 5.4.3.1.3;

– Distance trigger devices, if the field strength has to be sampled according to § 5.4.3.2.2.

The detailed setup and observable parameter depend on the radio service. While sometimes monitoring receivers with automatic gain / attenuator settings suffice, other services call for dedicated equipment like end user terminals or fast RF scanners with demodulation capabilities. Depending on the nature of the service, the number of frequencies of interest and the measurement device capabilities, the vehicle's speed has to be limited in such a way that the desired revisit intervals of the transmissions are achieved.

There are two basic alternatives for the measurement setup. The first option would be to use reference terminal equipment and the other option would be using standard monitoring equipment.

The use of reference terminals might provide only limited results since they merely indicate the behaviour of that very piece of equipment in the given environment. Parameters as the sensitivity of the receiver may not be known and therefore different from parameters assumed by the prediction tool.

On the other hand, such results might provide valuable information about network characteristics and quality of service by representing the user's perception of the network.

Simultaneous use of more than one terminal including different models may be considered to improve the reliability of such measurements or in order to investigate the coverage for different type of terminals such as automotive receivers, handheld and portable devices.

The other alternative, the use of standard monitoring equipment, can be used to evaluate technical parameters such as field strength. This should preferably be done under the same receiving conditions as assumed in the planning tool allowing further comparison between measurements and predictions.

The antenna is normally mounted on the roof of smaller vehicles for the coverage measurement of mobile reception whereas measurements in 10 m height may be appropriate for the determination of the coverage of broadcasting transmitters.

A receiver or spectrum analyser is used to provide field strength values for measurements in analogue networks. They are further used to identify any interference that could impede correct measurements.

The positioning system consists of a radionavigation satellite systems (RNSS) receiver or a dead reckoning system. Such systems are used to track the vehicle's movement based on an odometer and compass when the RNSS signal is lost, e.g. in a tunnel and prevents the system to produce too much data on a single location, e.g. at a traffic light, which might bias the results.

Obtaining results that are reliable and traceable also includes a proper documentation and consistent use of the measurement system. Depending on the number of staff required and the complexity of the measurement campaign, a training phase including practical training has to be taken into account.

The use of GNSS-based localization is usually not reliable in the case of indoor measurements. For this, the availability of floor plans is essential. Based on these, measurement points can be defined beforehand. This also enables planning regarding room access, especially e.g. in large office buildings or shopping centres. Typically, indoor measurements are made as walk tests where the measurement devices are carried in backpacks or with the devices placed on trolleys. Software packages for such measurements exist and should provide methods to import and scale floorplans, set markers and comments and offer suitable ways of presenting or exporting the results.

5.11.3.3 Execution phase

This phase is obvious. Especially during the start of that step, preliminary measurements shall be taken to check the proper functioning of the measurement setup throughout the measurement teams. It is beneficial that the data can be copied to the data processing office in the course of the execution phase. This does not only speed up the process, it also serves as a backup for the data gathered so far. Nowadays, options exist to send data into a central data-storage computer or a cloud-based system. Furthermore, if the system has the ability to distribute measurement setups via cloud services, necessary changes can be applied in a rapid fashion.

5.11.3.4 Data evaluation and reporting

In most cases, the data obtained in the field has to be post-processed. During that step, the data is evaluated e.g. in terms of location-based aggregation to match a grid laid out on the coverage prediction maps (see also: § 5.4.3.2.6). A typical grid-size is 100 × 100 meters, e.g. for broadcast or land mobile radio. Aggregation of parameters often includes the reduction of many values inside a square to one single value. Often, the median value can be regarded as a good representation, especially in regards of field strength (see § 5.4.1.1.4). Depending on the agreed coverage threshold, a certain maximum or the 9th percentile can be presented.

Nonetheless, it is important to keep in mind that these measurements are spot measurements. This implies that the data within one square has a location and time probability of 50% (see §§ 5.4.4.1 and 5.4.4.2).

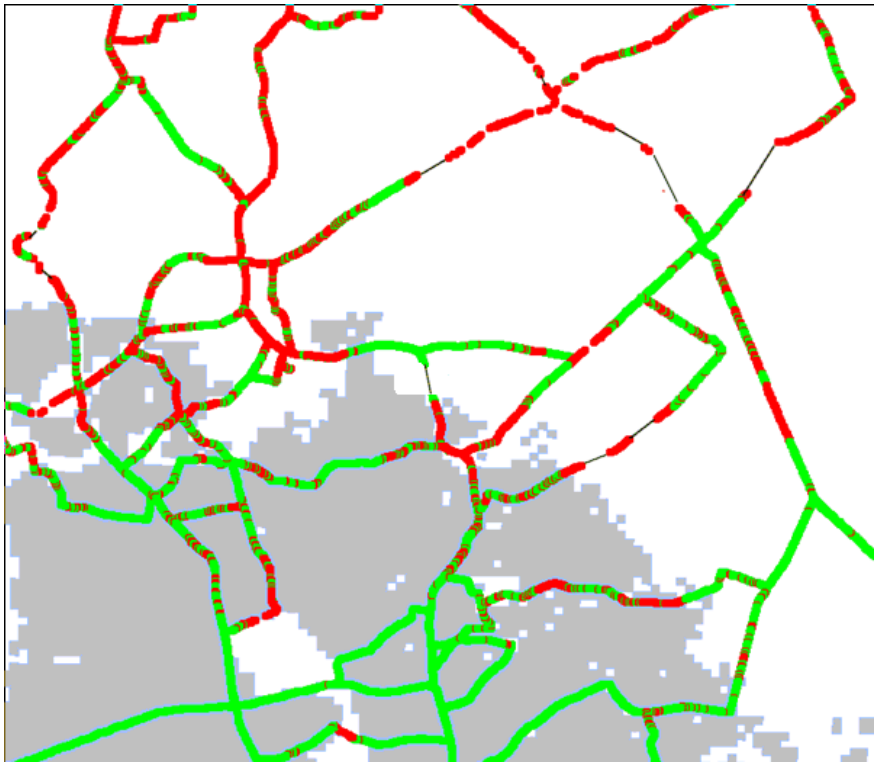
Comparison of the measured and predicted data is best done within a geographic information system (GIS, see § 7.2), as far as the measured samples were aligned with the coverage prediction's grid. Depending on the service, additional tools from measurement device manufacturers can assist that task.

For preliminary checks and stationary measurements, it usually suffices to evaluate the locations as single spots rather than resampling them onto a predefined grid. Care has to be taken to plot the measurement results in the form of separate points onto a map, as overlapping points hide information from others.

An example of a map-based evaluation is given in Fig. 5-118. The measured values are plotted right onto the map and coloured according to the operator's requirements: red dots indicate no coverage, green dots coverage and no dots (black, thin lines, right hand part of the figure) indicate that the measurement system wasn't able to get a reading from the instruments. This also implies the state 'no coverage'. The grey marked background indicates the areas deemed as "covered" by the planning bureau.

FIGURE 5-118

Visual comparison of predicted and measured data at the edge of a reference area



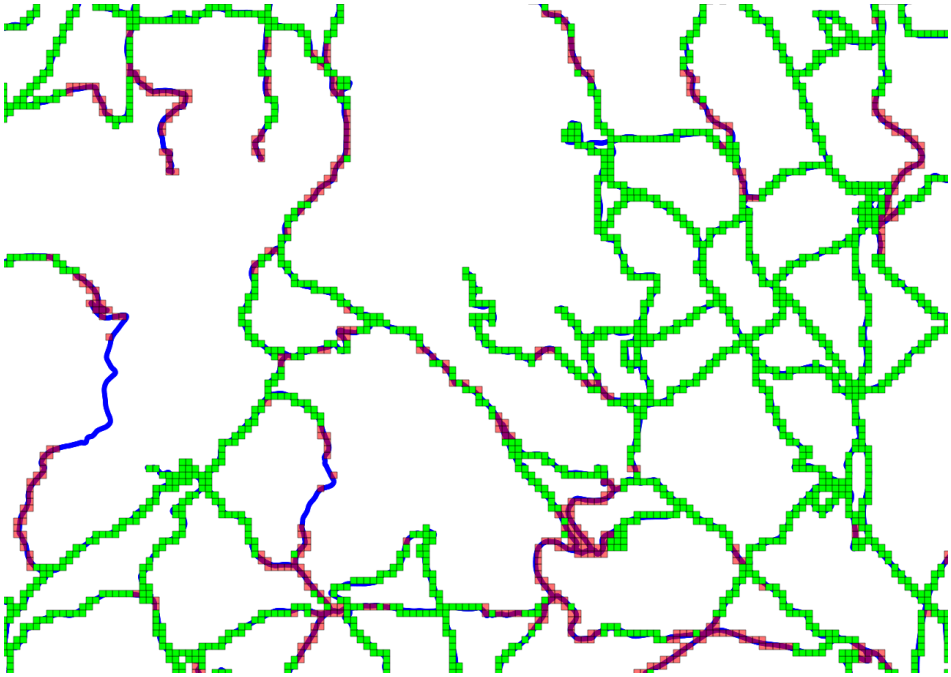
Spectrum-4.11-01

An example of a more sophisticated evaluation is shown in Fig. 5-119. Once again, the measurement results are on a red/green colour scale. In contrast to Fig. 5-118, the individual values have been processed to indicate the result for a small area. The resulting grid has been matched to the grid used by the planning bureau, so that prediction and measurement can be matched automatically.

Furthermore, the drive track is plotted with blue points to indicate the measurement route. This also indicates the spots where the system was not able to get readings from the instrument. The white background indicates that no measurement data is available.

FIGURE 5-119

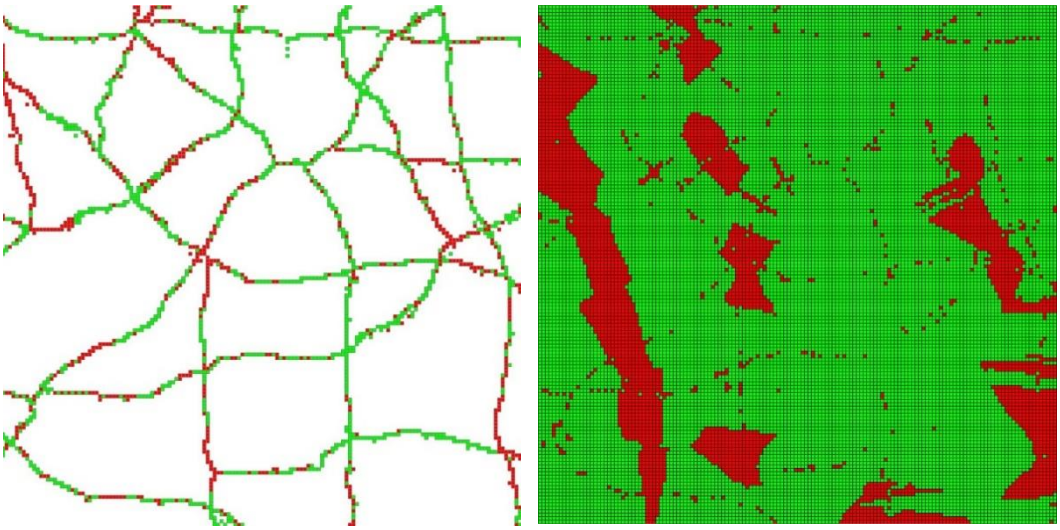
Measurement results as raster data



As field measurements can only cover a subset of locations, many grids on the map have no measurement results. Interpolation strategies can be used to guess on the situation within the blank areas. Specifically, the signal strength values at unsampled elements of the grid are predicted based on the existing samples. The underlying principle is that the existing signal strength data exhibits inherent spatial correlations. The interpolation accuracy is influenced by several factors, such as signal frequency, area size, grid configuration and density of measurements. The result is the better, the more environmental information (i.e. terrain, buildings and so on) is taken into account. As a result, the interpolated map offers a continuous representation of the estimated coverage situation, serving as a basis for evaluation and comparison purposes. An example of such an interpolated coverage measurement map is provided in Fig. 5-120. The lefthand subfigure shows the gridded measurement results aligned with the target grid. The righthand subfigure presents the coverage prediction map after the application of interpolation methods, where the previously unmeasured areas (blank regions) have been filled with interpolated values. This map provides an estimate of the whole coverage situation, with red and green indicating no coverage and coverage states, respectively.

FIGURE 5-120

Coverage measurement results and interpolated coverage map



Bibliography

BEREC [BEREC2020] BEREC Guidelines on Geographical surveys of network deployments;

ETSI TS 102 658 – Digital Private Mobile Radio (dPMR) using FDMA with a channel spacing of 6,25 kHz

ITU-R Recommendations

NOTE – In every case the latest edition of the Recommendation is encouraged to be used.

Recommendation ITU-R SM.1447 – *Monitoring of the radio coverage of land mobile networks to verify compliance with a given licence*

Recommendation ITU-R SM.1875 – *DVB-T coverage measurements and verification of planning criteria*

Recommendation ITU-R ITU-R V.573 – *Radiocommunication vocabulary*

ITU-T Recommendations

NOTE – In every case the latest edition of the Recommendation is encouraged to be used.

Recommendation ITU-T E.800-E.809 – *Terms and definitions related to the quality of telecommunication services*

Recommendation ITU-T E.802 – *Framework and methodologies for the determination and application of QoS parameters*

Recommendation ITU-T E.804 – *Quality of service aspects for popular services in mobile networks*

Recommendation ITU-T E.806 – *Measurement campaigns, monitoring systems and sampling methodologies to monitor the quality of service in mobile networks*

Recommendation ITU-T P.863 – *Perceptual objective listening quality prediction*

ITU-R Report

NOTE – In every case the latest edition of the Report is encouraged to be used.

Report ITU-R SM.2504 – *Methods for the estimation of coverage for terrestrial radio services based on population*

5.12 Unwanted emission measurements

5.12.1 Introduction

The measurement of unwanted emission is a common task for monitoring services. On the one hand, the goal of such measurements may be to check the conformity of an emission compared to an emission mask provided in a standard or a recommendation. On the other hand, such measurements could be required in the case of an interference caused by an unwanted emission.

Unwanted emissions are emissions out of the necessary bandwidth of a signal which include out of band emissions and spurious emissions.

Measurements of unwanted emissions may be difficult to carry out due to the fact that they require measurement equipment with extremely high dynamic range. According to the system to measure, ITU-R Recommendations and relevant system standards describe requirements for the optimum setup of the measurement.

5.12.2 Definitions and terminology

The following terms and definitions are extracted from the RR Edition 2024.

"1.144 *out-of-band emission: Emission* on a frequency or frequencies immediately outside the *necessary bandwidth* which results from the modulation process, but excluding *spurious emissions*."

"1.145 *spurious emission: Emission* on a frequency or frequencies which are outside the *necessary bandwidth* and the level of which may be reduced without affecting the corresponding transmission of information. Spurious emissions include harmonic *emissions*, parasitic *emissions*, intermodulation products and frequency conversion products, but exclude *out-of-band emissions*."

"1.146 *unwanted emissions:* Consist of *spurious emissions* and *out-of-band emissions*."

"1.146A *out-of-band domain* (of an emission): The frequency range, immediately outside the *necessary bandwidth* but excluding the *spurious domain*, in which *out-of-band emissions* generally predominate. *Out-of-band emissions*, defined based on their source, occur in the out-of-band domain and, to a lesser extent, in the *spurious domain*. *Spurious emissions* likewise may occur in the out-of-band domain as well as in the *spurious domain*."

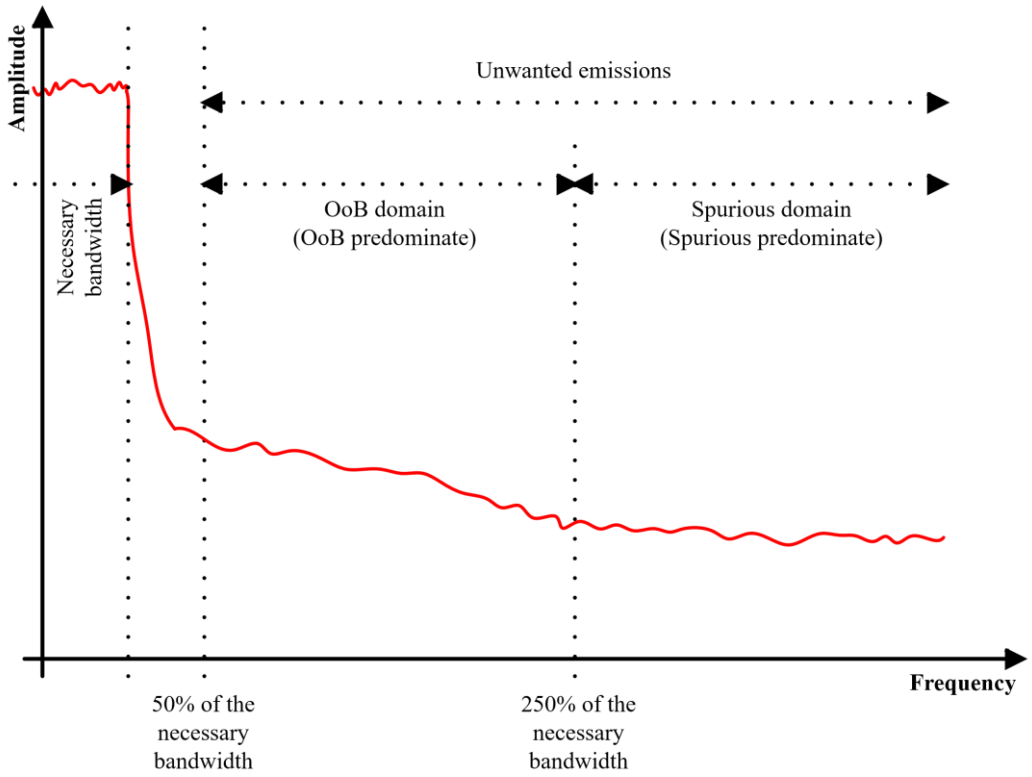
"1.146B *spurious domain* (of an emission): The frequency range beyond the *out-of-band domain* in which *spurious emissions* generally predominate."

"1.152 *necessary bandwidth:* For a given *class of emission*, the width of the frequency band which is just sufficient to ensure the transmission of information at the rate and with the quality required under specified conditions."

Figure 5-121 illustrates those definitions. The boundary between the out-of-band and the spurious domain is provided for information (250% is commonly used for radar systems for example).

FIGURE 5-121

Illustration of the OoB and spurious domain



5.12.3 Frequency ranges of unwanted emissions

Unwanted emissions are divided into two domains:

– Out-of-band domain;

– Spurious domain.

To distinguish the two domains, the boundary between them should be defined based on RR's Annex 1 to Appendix **3**. Some guidelines are provided in Recommendation ITU-R SM.1539: Tables 1 and 2 of Annex 1 provide values to assess the frequency separation between the centre frequency of the signal and the boundary between out-of-band and spurious domain. This frequency separation is defined by two thresholds which depend on the nature of the signal (narrowband (B_L) and wideband (B_U) emission). Practically, for very narrowband emissions, the out-of-band domain is relatively wider compared to the necessary bandwidth (where the boundary to the spurious domain starts at an offset of 2.5 times the necessary bandwidth). Inversely, if the emission is very wide, the out-of-band domain is also narrower compared to the necessary bandwidth.

When the boundary between OoB and spurious domain is determined, the frequency range of the measurement should be defined. Measurements of unwanted emissions have to be carried out covering a wide frequency range. Table is extracted from Recommendation ITU-R SM.329 and provides the frequency range to analyse according to the frequency of the fundamental of the signal.

TABLE 5-20

Frequency range for measurement of unwanted emissions

Fundamental frequency	Frequency range for measurements	
	Lower limit	**Upper limit**
9 kHz – 100 MHz	9 kHz	1 GHz
100 MHz – 300 MHz	9 kHz	10th harmonic
300 MHz – 600 MHz	30 MHz	3 GHz
600 MHz – 5.2 GHz	30 MHz	5th harmonic
5.2 GHz – 13 GHz	30 MHz	26 GHz
13 GHz – 150 GHz	30 MHz	2nd harmonic
150 GHz – 300 GHz	30 MHz	300 GHz

Note that the measurement should include the entire harmonic band and not be truncated at the precise upper frequency limit stated.

An example for the boundary between necessary bandwidth and the two types of unwanted emissions is pictured in Fig. 5-121. The captured signal is a 10 MHz LTE signal. It consists of 600 subcarriers, each with 15 kHz bandwidth. Therefore, the necessary bandwidth is 9 MHz and the OoB domain starts 4.5 MHz above the upper edge of the signal.

5.12.4 Measurements in the spurious domain

Usually spurious emissions are weak signals and equipment has to fulfil stringent requirements to measure them. The general approach is to attenuate the main signal with the use of filters as much as possible and scan the required frequency range (see Table 5-20) with the measurement bandwidth stated in the relevant Standard or Recommendation. Usually this frequency range is far too wide to record it in one single step (e.g. one sweep with an analyser). Current spectrum analysers display the spectrum using a raster scan display. Characteristic for these displays is that the number of pixels in the level axis as well as in the frequency axis is limited. This leads to limited resolution for both level and frequency. The limited frequency resolution may cause a loss of signals on screen, when measuring wide frequency ranges with narrow resolution bandwidths (narrower than one pixel). Some equipment allows that the number of sweep points may be specified by the user. The higher the displayed point number the higher is the frequency resolution of the measurement.

However, a number of points higher than the screen resolution do not show all results on the built-in screen. The increased frequency resolution is only usable if the trace data is exported and post-processed by software.

In most cases, multiple measurements have to be performed, each one covering a certain part of the total frequency range.

5.12.5 Measurements in the out-of-band domain

For most of the services, the result of the measurement of unwanted emissions is either expressed as the mean power (r.m.s.) emitted in channels other than the assigned channel, or in spectrum power density (or the power of discrete components) at frequencies above and below the limits of the necessary bandwidth. To determine the conformance of a signal regarding the out-of-band emissions, three different types of measurement could be defined:

– the adjacent channel and alternate adjacent channel power method;

– the spectrum mask method;

– the fixed-level measurement method.

These methods are described below.

Since out-of-band emissions are associated with low-level spectral components of any class of emission at its both edges, special attention should be paid to the aspects of the influence of interference and noise on the measurement results in the conditions of operation of spectrum monitoring stations. In many cases, remote

measurements cannot be carried out at all and measurements are required near the transmitters using mobile spectrum monitoring stations. And even in such circumstances difficulties with measurements may arise. In such cases may be useful the provisions given in Section 4 of Annex 2 to Recommendation ITU-R SM.443-4 concerning the measurement of x-dB bandwidths under conditions of interference.

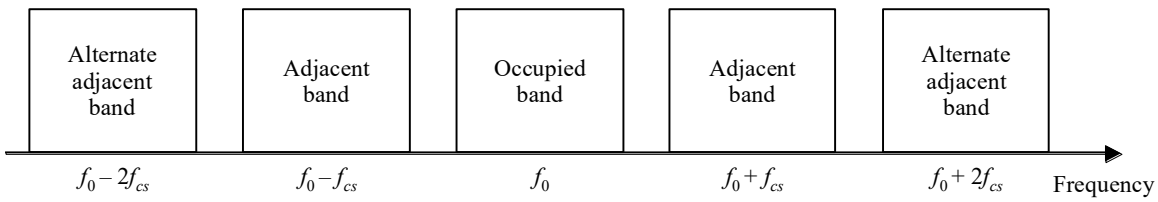
It should also be taken into account that in spectrum monitoring conditions, measurements are carried out on signals of real messages and this may cause great variability of the reproduced spectra, including out-of-band ones, of a number of classes of emissions, especially single-channel ones under transmission of speech signals. Therefore, for better reproduction of the out-of-band spectrum envelope, it is desirable to use the "maximum hold" mode when recording a sufficiently large number of spectrum records.

5.12.5.1 Adjacent channel power measurements

This method consists in measuring the mean power of a signal in bands illustrated in Fig. 5-122 and Fig. 5-12.

FIGURE 5-122

Power measurements bands



f_{cs}: Spacing between assigned frequencies.

Spectrum-4.12-02

This measurement is most commonly performed using a spectrum analyser. Most modern analysers have a built-in measurement function that measures the in-band power and the power in neighbouring channels at the same time. The channel bandwidth and channel spacing has to be entered manually. Their values can be taken from the relevant standard, national or international channelling plans, whichever is applicable to the service. In some systems, the channel spacing is wider than the channel bandwidth (guard bands), but most analysers allow to enter them separately.

The mean powers of the requested channels are measured by integrating the spectral power density in each channel separately after the total spectrum has been recorded with a relatively narrow resolution bandwidth (RBW). As a rule of thumb, the optimum RBW is about 1/100 to 1/500 of the total span. Care must be taken not to use the peak detector for this measurement.

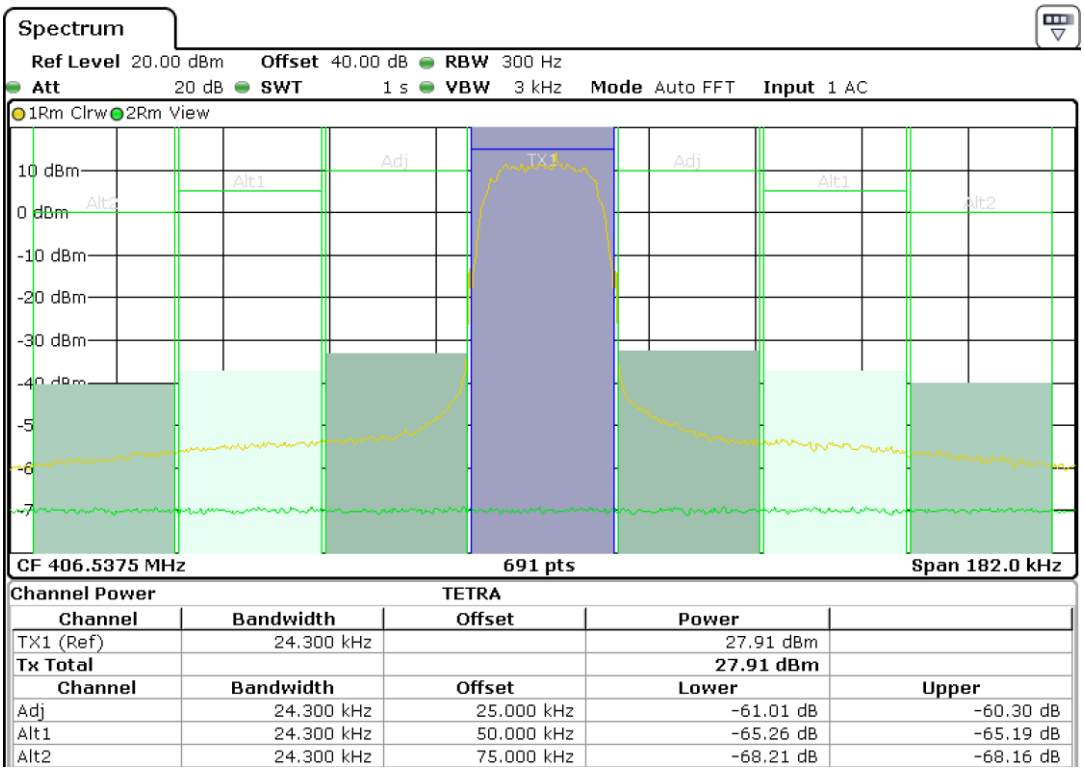
In most of the services, depending on the measurement equipment, the sample or RMS detector has to be used and the trace mode must be clear/write. Without additional functions such as a “gated trigger”, this measurement can therefore only be used with continuous emissions and is not possible with TDMA systems. However, it should be noted that some systems (as radars for example) require that the measurement is performed with a peak detector and the maxhold trace.

The most common practical problem occurring in this measurement is that the power in the adjacent or alternate channels is below or close to the noise floor of the measurement receiver/analyser. To ensure that the result is valid, a preliminary measurement with the transmitter switched off should be made, using the same equipment settings as for the actual measurement. The displayed adjacent and alternate channel powers are noted. The actual measurement is valid if the adjacent and alternate channel powers with the transmitter switched on are at least 8 dB above the values of the preliminary measurement. This will reduce the error to at least 1 dB or less, cf. section 5.3.11.2.

Figure 5-123 gives an example of the adjacent channel power measurement of a TETRA handheld transmitter. The lower trace is the system noise level (DANL, displayed average noise level) when the transmitter under test is switched off.

FIGURE 5-123

Adjacent channel power measurement example



5.12.5.2 Spectrum mask measurements

This method may be applied for OoB or spurious emissions. It is based on the comparison of the spectrum power density of an emission in a certain measurement bandwidth with a spectrum mask provided in recommendations or standards.

Strictly taken, this method only works if a continuous relative spectrum mask using the same reference bandwidth is defined. In many standards, however, the out-of-band limits are given as a mixture of absolute and relative levels. This is to ensure that the maximum radiated power in adjacent bands does not exceed certain values, regardless of the total power radiated by the transmitter. In these cases, a mask used to compare the measured spectrum with has to be calculated first (using relative levels). This mask, however, is then only valid for a certain output power of the transmitter.

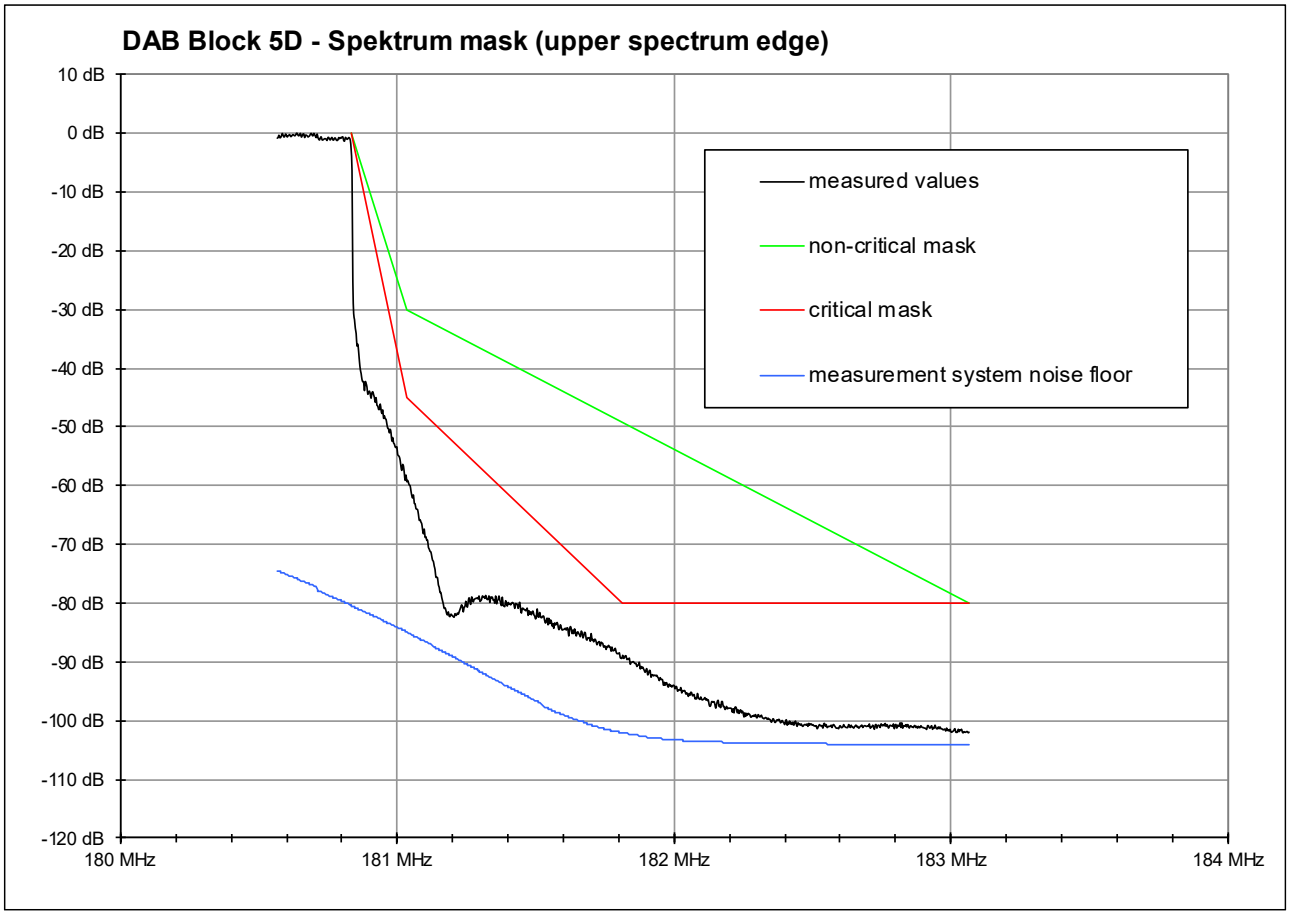
Many standards apply different reference bandwidths for different parts of the OoB spectrum. In these cases, the spectrum mask method will not produce accurate results according to the standard. However, because emissions in the out-of-band domain usually have a continuous spectral density distribution (i.e. no distinct frequencies), the method can still be applied with reasonable accuracy if the calculation of the relative spectrum mask includes the necessary bandwidth correction as demonstrated in § 5.3.9.

The results of the spectrum mask measurement should be presented in terms of dBsd, dBc or dBpp (see Recommendations ITU-R SM.329 and ITU-R SM.1541).

Figure 5-124 shows an example result of an out-of-band emission measurement on a digital audio broadcast (DAB)-transmitter using the spectrum mask method.

FIGURE 5-124

Out-of-band emission measurement of a DAB transmitter



5.12.5.3 Fixed-levels measurements

Currently, spectrum masks are provided in the ITU-R documentation only for a relatively small number of used classes of emission. For the remaining classes, measurements of out-of-band emissions can be performed based on the measurement of the x-dB bandwidth values at fixed levels of −40, −50 and −60 dB in accordance with the data provided in Report ITU-R SM.2048. The Report contains tolerances for the bandwidth values at the specified levels for about 180 emission classes. Section 5 of the Report provides a detailed measurement methodology. Although it is presented for the case of measurements in stationary conditions using test signals, a number of its provisions, in particular those concerning the setting of zero reference levels and spectrum analyser parameters, are also quite acceptable for spectrum monitoring conditions.

5.12.6 Equipment requirements, setup and measurement limitations

The measurements of unwanted emissions require a high dynamic range which might be out of equipment specifications for a given measurement setup. So, to perform such measurement special care should be taken to optimize the measurement setup.

5.12.7 Optimizing the dynamic range of the measurement setup

In order to obtain the maximum dynamic range for unwanted emission measurements, the measurement receiver or spectrum analyser has to be loaded with the maximum possible level at the input mixer, without compressing the transmit signal. The RF attenuation has to be set to the minimum possible value that does not result in compression of the signal path.

The equipment noise floor is a limitation. The noise floor of a spectrum analyser or receiver is usually specified as the Displayed Average Noise Level (DANL) in 10 Hz or 1 Hz resolution bandwidth. This characteristic represents the capacity of an analyser to measure a weak signal and the value of this characteristic limits the minimum of discernible signal on the equipment. The inherent noise power of a spectrum analyser or receiver

is dependent on the resolution bandwidth setting and the reference level setting. The lower the RBW, the lower is the inherent noise power of the analyser. Nevertheless, the RBW is usually fixed in the relevant Recommendation or standard, in accordance with the type of signal to measure.

5.12.8 Required equipment

The general approach to measure unwanted emissions is the use of a spectrum analyser. However, measurement receivers may also be used. One practical way, especially for spectrum mask measurements in the out-of-band domain, is a computer controlled scan over the frequency range of interest, using a measurement receiver. The preselection filters usually employed in measurement receivers often provide a higher dynamic range than the use of spectrum analysers.

To lower the inherent noise power in the unwanted emission measurement, internal or external low noise amplifiers (LNA) may be used. However, the maximum measurable level without overloading the equipment then depends on the capabilities of the LNA rather than the spectrum analyser or receiver itself. Care must be taken not to overload any component of the measurement system.

If the measurement setup allows a direct measurement with a sufficient dynamic range then the measurement may be carried out directly and the result may be processed without any post-treatment.

In many cases the spectrum mask spans a level range of 100 dB or more, or the spurious emissions should be suppressed by 100 dB. Measurements in these domains are only valid when the receiver noise is still at least 10 dB below the weakest signal component to measure. This would require a measurement dynamics of at least 110 dB which is beyond the specification of any spectrum analyser or receiver. As the input of the spectrum analyser is loaded with high level of the signal to measure, signal distortion might be observed due to non-linearity in the spectrum analyser signal path. In particular, well-known spurious products are third order intermodulation products and harmonic distortion products. In these cases, the main signal in the wanted channel has to be suppressed by filters. For frequencies above 1 GHz, YIG filters are most appropriate as they can be tuned electrically and only pass the frequency range currently measured. The unwanted emissions are then measured through the filter and the results are corrected by the (measured) filter attenuation. This is usually done by post-processing software.

Moreover, for any desired signal, where the output amplitude changes with time (e.g. non constant envelope modulation), ten or more averaged measurements may be used for consistency.

5.12.9 Practical aspects of the measurement

Usually the relevant standard or recommendation requires a conducted measurement at the transmitter output. However, if the measurement is performed off air, the results have to be measured as field strength values. This means that different measurement antennas with different correction factors may have to be used. Care should be taken that measurement antennas are only used inside their defined operational range.

One of the main practical problems, especially when performing these measurements off air, is that signals from other transmitters, that cannot be fully suppressed, will be seen in the result. To minimise their influence, two consecutive measurements of each part of the frequency range may be done: during the first measurement the investigated transmitter is switched off, during the second one it is switched on. Emissions showing up in both scans are due to external signals, emissions showing only in the second scan may be due to spurious emissions from the transmitter under test. Considering that even external emissions are not always active, this approach delivers better results if there is less time difference between scan one and two. If the emission from the transmitter under test is pulsed, the pauses can be evaluated to detect external signals. This approach, however, requires that the measurement equipment is time-synchronized with the transmitter under test.

Spectrum mask measurements in the OoB domain are covered in detail in Annex 1 of Recommendation ITU-R SM.1541.

A further example of unwanted emission measurements of radar systems is described in § 6.5.

The measurement of unwanted emissions in the spurious domain is largely covered in Annex 2 to Recommendation ITU-R SM.329.

Example:

As an example for the measurement challenges and possible solutions, a measurement at the output port of an LTE base station is described. The device under test is an LTE base station operating in the E-UTRA band 72 (461-466 MHz downlink). The channel bandwidth is 1.4 MHz with a transmit power of 46 dBm.

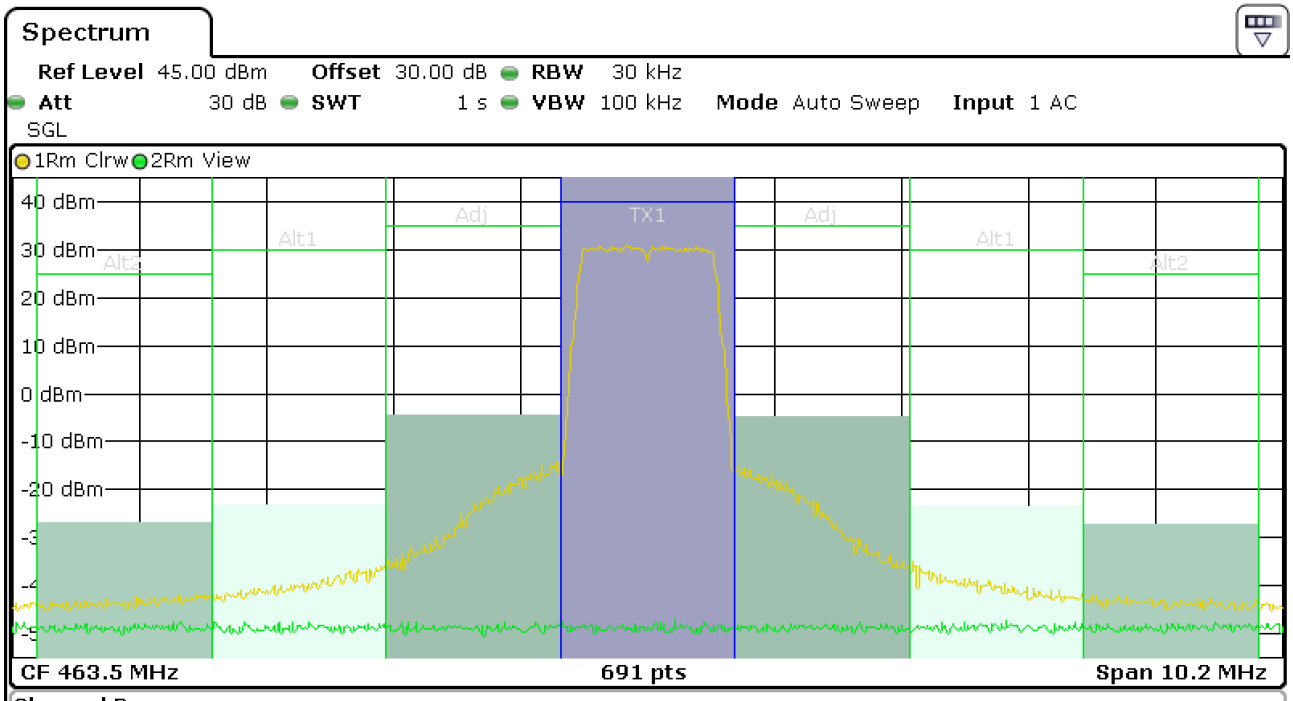
ETSI TS 136 141 specifies measurements procedures and limits for ACLR, OoB emissions and spurious emissions. For the ACLR a limit of 44.2 dB below the transmitting channel is defined. If we consider the mentioned signal to noise ratio of at least 8 dB this needs a measurement dynamic of at least 50 dB. This is well within the capability of current spectrum analysers. However, the transmit power of 46 dBm requires a power attenuator to stay within the rated input power of the spectrum analyser.

Figure 5-125 shows the measurement. The green trace shows the noise of the measurement setup. It is easy to spot that the signal to noise ratio is below 8 dB for the outer channels. The ACLR limit of 44.2 dB is achieved but this measurement does not allow for a result with a certainty better than 1 dB.

To get a better look at the unwanted emissions in the operating band, the method described in § 5.12.8 is used. A band reject filter is tuned to suppress the wanted signal.

FIGURE 5-125

Adjacent channel power measurement of a 1.4 MHz LTE signal

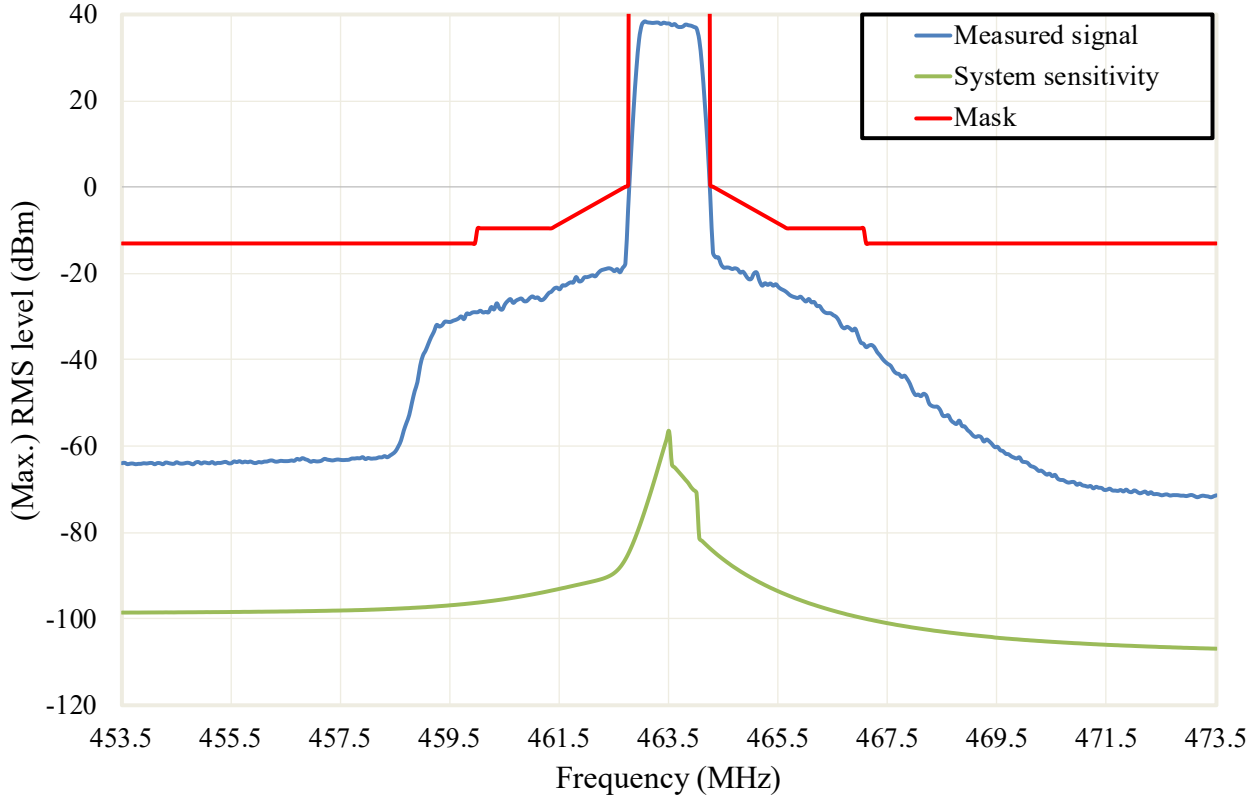


Channel Power

Channel	Bandwidth	Offset	Power	
TX1 (Ref)	1.400 MHz		45.43 dBm	
Tx Total			**45.43 dBm**	
Channel	**Bandwidth**	**Offset**	**Lower**	**Upper**
Adj	1.400 MHz	1.400 MHz	-49.98 dB	-50.41 dB
Alt1	1.400 MHz	2.800 MHz	-68.54 dB	-68.84 dB
Alt2	1.400 MHz	4.200 MHz	-72.41 dB	-72.53 dB

FIGURE 5-126

Spectrum mask measurement of a 1.4 MHz LTE signal



The spectrum shown in Fig. 5-126 is split up into two parts, because the bandwidth of the used band reject filter exceeds the bandwidth of the wanted signal. With this method the result is a spectrum measurement with a high resolution and a dynamic range of approximately 130 dB. This is an improvement by about 50 dB compared to the previous ACLR measurement. The spectral resolution is easily adjustable however the achievable dynamic range is depending on the used spectrum analyser and the characteristics of the filter used.

The channel power values can be calculated from this measurement using the integration bandwidth method described in § 5.3.10. Because of the better signal to noise ratio the ACLR values can be stated without the previous inaccuracy.

ETSI TS 136 141 Table 6.6.3.5.1-1 defines a spectrum mask for the OoB emissions. The mask has absolute limits and is pictured in Fig. 5-126 together with the spectrum and the system sensitivity.

Bibliography

Recommendation CEPT (2012), REC(02)05, "Unwanted emissions".

ITU-R Recommendations

NOTE – In every case the latest edition of the Recommendation is encouraged to be used.

Recommendation ITU-R SM.328 – *Spectra and bandwidth of emissions*

Recommendation ITU-R SM.329 – *Unwanted emissions in the spurious domain*

Recommendation ITU-R SM.1541 – *Unwanted emissions in the out-of-band domain*

Recommendation ITU-R SM.1792 – *Measuring sideband emissions of T-DAB and DVB-T transmitters for monitoring purposes*

ITU-R Reports

NOTE – In every case the latest edition of the Report is encouraged to be used.

Report ITU-R SM.2048 – *Use of the x dB bandwidth criterion for determination of spectral properties of a transmitter in the out-of-band domain*

Report ITU-R SM.2421 – *Unwanted emissions of digital radio systems*.

CHAPTER 6

Specific monitoring systems and procedures

TABLE OF CONTENTS

Page

6.1 Monitoring of spacecraft emissions 431
- 6.1.1 Tasks and measurements to be performed 431
- 6.1.2 Measurement techniques 434
- 6.1.3 Equipment and facility requirements 450
- 6.1.4 Documentation and database support to space monitoring 458
- 6.1.5 Identification of space stations and geolocation of earth stations 459
- 6.1.6 Technical solutions by examples 464
- 6.1.7 Monitoring results by examples 494
- 6.1.8 References 501

6.2 Monitoring of terrestrial broadcast emissions 502
- 6.2.1 Introduction 502
- 6.2.2 Broadcast standards and measurements 504
- 6.2.3 Coverage measurements 509
- 6.2.4 Specific instruments used on broadcasting monitoring 509
- 6.2.5 References 512
- 6.2.6 Other references 514
- 6.2.7 Abbreviations/Glossary 514

6.3 Monitoring of cellular systems 515
- 6.3.1 Introduction 515
- 6.3.2 General description of the IMT systems and common monitoring procedures 516
- 6.3.3 Common interference sources 519
- 6.3.4 2G/GSM 520
- 6.3.5 3G/UMTS 525
- 6.3.6 4G/LTE 530
- 6.3.7 5G/NR 538
- 6.3.8 Coverage measurements 547
- 6.3.9 References 553
- 6.3.10 Abbreviations/Glossary 554

6.4 Microwave links and satellite uplinks 555
- 6.4.1 General introduction 555
- 6.4.2 Use of microwave links 556
- 6.4.3 General techniques for measurement 560
- 6.4.4 Equipment for monitoring vehicles 563
- 6.4.5 Fixed-satellite service sharing with the fixed service 566

6.4.6 Safety 573
6.4.7 References 574
6.4.8 Bibliography 574
6.4.9 Abbreviations/ Glossary 574
6.5 Monitoring of radar emissions 575
6.5.1 Introduction 575
6.5.2 Radar basic principle 575
6.5.3 The radar range equation 576
6.5.4 Main components of radar systems 576
6.5.5 Application of radar 577
6.5.6 Basic radar technologies 578
6.5.7 Types or classification of radars 578
6.5.8 Main frequency bands for radar systems 581
6.5.9 Instrument to measure radar signals 582
6.5.10 Measurement of radar signals 583
6.5.11 Abbreviations/Glossary 594
6.5.12 References 594
6.6 Measurements of RF-EMF human exposure levels 595
6.6.1 Introduction 595
6.6.2 ITU three sectors, activities on EMF 596
6.6.3 ICNIRP Guidelines 596
6.6.4 Instruments for RF-EMF measurements 600
6.6.5 Measurement procedures 606
6.6.6 Uncertainty 613
6.6.7 Reporting 614
6.6.8 References 614
6.6.9 Abbreviations/Glossary 615
6.7 Radio noise measurements 615
6.7.1 Introduction and background 615
6.7.2 Sources of radio noise 616
6.7.3 Components of radio noise 618
6.7.4 Key parameters 619
6.7.5 Measurement types 619
6.7.6 Measurement locations and frequencies 619
6.7.7 Examples of result presentation 620
6.7.8 ITU radio noise databank 623
6.7.9 References 623
6.7.10 Abbreviations/Glossary 624

6.1 Monitoring of spacecraft emissions

6.1.1 Tasks and measurements to be performed

A monitoring service responsible for the enforcement of domestic laws and regulations and engaged in international monitoring, pursuant to RR Article **16**, would normally participate in the monitoring of emissions from space stations as a normal and necessary extension of regular monitoring facilities, techniques and operations.

In general, the tasks carried out by a radio monitoring station for space services do not differ from those of a radio monitoring station for terrestrial services. However, radio monitoring for space services requires the use of relatively more complex measuring equipment, such as more complex antenna systems, as well as differing monitoring and measurement procedures. This is primarily because space stations are located aboard satellites whose positions are time dependent, except for those in tightly controlled geostationary orbits. Basic knowledge of the orbits of such objects is an important precondition for any kind of observations and measurements of them.

Because space monitoring differs from terrestrial monitoring in both measurement techniques and terminology, that which provides the space function is known as a "monitoring station for space radio services". The functions of such a station can be outlined as follows:

– regular and systematic observation of the radio frequency spectrum with the aim of detecting and identifying space station emissions;
– determination of occupancy and percentage use of transponders or space station transmitters;
– measurement and recording of the characteristics of space station emissions;
– investigation and elimination of harmful interference caused by space station emissions, if appropriate, in cooperation with terrestrial and other monitoring stations for space services;
– investigation and elimination of harmful interference to the frequencies used by a space station caused by the emissions of terrestrial stations, unknown earth stations, or other satellites, e.g. by observing and measuring a transponder, interfering signal in a similar manner as for legitimate space station emissions; (see § 6.1.1.1);
– measurements and recordings for technical and scientific projects;
– detection of illicit use of transponders and identification of its source(s);
– using special satellite techniques to locate emitters on Earth;
– pre-launch monitoring, during the pre-phase of the launch of a satellite, to monitor the frequencies used for telemetry, telecommand and tracking with respect to the orbit position. This pre-launch monitoring will facilitate a saver launch and early orbit phase, including position.

Space radiocommunication services are defined in Article **1**, Section III, of the Radio Regulations. Additional terms and definitions concerning space systems, services and stations relating to space radiocommunications are defined in Recommendation ITU-R S.673.

If all types of spacecraft have to be observed, the antenna system must be capable of tracking low orbiting and highly elliptical orbiting satellites as well as being able to point accurately at GSO satellites.

The basic functions of a ground-based satellite monitoring station are described in Report ITU-R SM.2424. Overall system cost must be balanced against the following design choices made for the provision of the above-mentioned capabilities:

– frequency coverage,
– system sensitivity,
– antenna slewing rate,
– antenna pointing accuracy,
– ease of changing antenna feed hardware if necessary,
– receiving bandwidth capability,

– degree of sophistication of signal analysis instrumentation,
– geolocation accuracy of transmitters on Earth and
– degree of automation of measurements.

A highly automated and sophisticated spacecraft monitoring system, fully steerable, with continuous frequency coverage across the 1-30 GHz spectrum, for example, and sensitive enough to give carrier-to-noise ratios of at least 26 dB on all signals of interest would be ideal. However, as a practical matter in this example, incremental improvements in sensitivity come at costs that rise almost exponentially. Each administration must, therefore, analyse its own priorities and internal needs with regard to spectrum management and decide priorities for monitoring of space services.

Table 6-1 provides an overview of factors to consider when conducting monitoring activities involving satellite signals. The Table is organized by satellite type and signal path (uplink to satellite, downlink from satellite).

TABLE 6-1

Factors to be considered when conducting monitoring activities involving satellite signal

Satellite type	Satellite spacecraft emissions (downlinks)	Satellite earth station emissions (uplinks)
Geostationary-satellite orbit (GSO)	Monitoring tasks are usually conducted from fixed monitoring stations, due to their superior antenna performance and system sensitivity. The antenna positioning required for GSO satellites is along the equatorial arc only.	Monitoring of emissions from satellite earth stations to GSO satellites, including very small aperture terminals (VSATs) found on many businesses, are accomplished by mobile vehicles operating in the appropriate frequency range. The high directivity of typical satellite earth station antennas requires the measuring equipment to be near the transmitting antenna or somewhere in the main beam.
Non-geostationary-satellite orbit (non-GSO)	Monitoring tasks are usually conducted from fixed monitoring stations with antenna tracking capability (though mobile systems with tracking capability could be used). The monitoring station antenna must continuously track the satellite position based on one of several methods of satellite tracking covered later in the chapter. For tracking non-GSO satellite constellation, the phased array antennas could be a beneficial supplement to the mechanical antennas.	Monitoring of emissions from satellite earth stations or terminals to non-GSO satellites are accomplished by mobile vehicles. As with the GSO case, the antenna directivity requires the measuring equipment to be near the transmitting antenna or somewhere in the main beam. An additional factor is that the transmitting antenna will be moving to follow the satellite orbit, complicating measurements of amplitude related parameters.

6.1.1.1 Types of measurements

For the satellite monitoring, the following main measurements and determinations are to be carried out:

– Frequency.
– Doppler frequency.
– Power flux-density (pfd) in reference bandwidth and total.
– e.i.r.p., channel e.i.r.p. and carrier e.i.r.p.
– Carrier C/N_0.
– Bandwidth and carrier bandwidth.
– Out-of-band spectrum measurements.
– Transmission characterization.
– Identification of modulation type and multiple access type.
– Spectrum observations recording and I/Q data storage.

– Fast spectrograms to visualize fast slots drifts and sweeping signals.

– Polarization measurements.

– Satellite orbit position (orbital position accuracy of at least 0.1°).

– Received signal-to-noise ratio.

– Monitoring of non-GSO active/non-active satellites for equivalent power flux-density (epfd) calculations.

– GSO arc avoidance checks.

– Non-GSO pfd measurements for calculations of epfd.

6.1.1.2 Types of interference caused by satellite systems

– Adjacent channel interference.

– Co-channel interference.

– Cross-channel (cross-polarization) interference.

– Adjacent system interference.

These types of interference are produced at the input of the receiving earth station by carriers transmitted by either the satellite of the considered system (consisting of an earth station and satellite) or by a satellite of another system.

Adjacent channel interference

This type of interference is produced by carriers transmitted from the satellite to earth stations in the same system, located in the same spot beam as the earth station under consideration, which is further below in the text referred to as the victim earth station, transmitted at different frequencies but at the same polarization.

In FDMA and TDMA access schemes, these carriers interfere with the victim carrier because of the non-ideal performance of the filter of the transmitted earth station.

Co-channel (co-polarization) interference

Co-channel interference is produced by carriers, transmitted by the satellite to earth stations of the same system, at the same frequency and at the same polarization as the victim carrier.

These interfering carriers are sent to earth stations, located in a different spot beam from the victim earth station in FDMA and TDMA, but they are located in the same spot beam as the victim earth station in CDMA.

In FDMA and TDMA, this interference is limited by the satellite antenna roll-of the adjacent spot beam in the direction of the victim earth station whereas in CDMA it is limited by code correlation properties.

Cross-channel interference

This type of interference is produced by carriers, transmitted by the satellite to earth stations of the same system, at the same frequency and at the orthogonal polarization as the victim earth station carrier.

These interfering carriers are sent to earth stations located in a different spot beam as the victim earth station if single polarization is used, but to earth stations located in the same spot beam as the victim earth station for dual polarization systems.

For systems with single polarization this interference is limited by the satellite roll-of the adjacent spot beam in the direction of the victim earth station and by the isolation in polarization of the satellite antenna. In case of polarization re-use, it is limited by the polarization isolation of both satellite and earth station antennas only.

Adjacent system interference

This interference is produced by carriers transmitted by another satellite to earth stations of another satellite communication system, transmitting at the same frequency and polarization as the victim earth station carrier.

This interference is limited by angular separation of the two satellites from the victim earth position.

6.1.2 Measurement techniques

6.1.2.1 General

The main factors which necessitate different techniques for the monitoring, observation and measurement of emissions from space stations as compared to emissions from fixed or mobile radio stations on or near the Earth are:

– the difference between the received and the transmitted frequency, and the varying nature of the received frequency, caused by the Doppler shift effect, particularly for satellites not in GSO orbit;

– the weak pfd at the Earth receiving point, due to distance and generally low transmitter power;

– the relatively short time that a signal from a near-Earth orbiting satellite is receivable at a fixed monitoring point;

– the continual direction changes that have to be made to highly directional earth station antennas used to receive emissions from space stations not in GSO orbit.

6.1.2.2 Frequency measurements

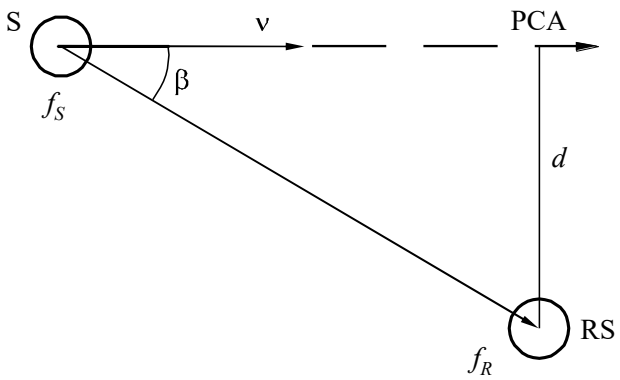
In the case of GSO space stations, the same frequency measurement methods can be applied as they are used for terrestrial stations. These methods are discussed in detail in § 5.2.

6.1.2.2.1 The Doppler shift effect

When there is a relative velocity between the transmitting space station and the monitoring station, a difference of frequency proportional to the relative velocity arises between the transmitted and received signal owing to the Doppler shift effect. Equations (6-1) and (6-2) are derived from Fig. 6-1.

FIGURE 6-1

Principle relations in case of Doppler shift effect



Spectrum-5.1-01

$$f_R = \frac{c f_S}{c - v \cos\beta} \tag{6-1}$$

$$\left(\frac{d f_R}{dt}\right)_{max} = \frac{f_S}{c} \cdot \frac{v^2}{d} \tag{6-2}$$

where:

S: satellite

RS: receiving station

PCA: position of closest approach

f_S: transmitting frequency

f_R: receiving frequency

v: velocity of satellite

d: minimum distance at pass over

c: propagation velocity of electromagnetic waves

β: angle between flight direction and line of sight direction to receive station.

The equations lead to the following findings:

– the received frequency is higher than the source frequency when the satellite is approaching the monitoring station;

– a measured frequency is equal to the correct satellite source frequency only at the time of closest approach (TCA) which coincides with the position of closest approach (PCA);

– during the TCA the maximum rate of change of frequency (MRCF) is to be observed, which gives the slope of the inflectional tangent$(d_{fR}/dt)_{max}$;

– the received frequency is lower than the source frequency when the satellite is receding from the monitoring station;

– the Doppler shift effect is proportional to the satellite's source frequency and depends on the relative velocity between the source and the monitoring station.

6.1.2.2.2 Measurement method

The achievable accuracy of a determined frequency emitted by a satellite depends on satellite orbital parameter, the propagation path, the measuring equipment and the method of evaluation. The measurement of the frequency of a non-GSO orbiting satellite is an indirect procedure, which first requires the registration of the Doppler shift, followed by the evaluation of the Doppler curve.

To obtain adequate measurement an automated measuring method is preferred. See § 6.1.6.1 for details of a possible technical solution.

6.1.2.2.3 Frequency calculation procedure and measurement accuracy

By using graphical methods, it is possible to determine the satellite frequency, the TCA and the MRCF (Fig. 6-2). The achievable frequency measurement accuracy is $\pm 1 \times 10^{-7}$ Hz.

A modified method enables the degree of accuracy to be improved. By a single differentiation of the Doppler frequency curve with respect to time, a parabola is obtained, the vertex of which indicates the TCA and also the transmitter source frequency of the satellite.

For the construction of the parabola, it is sufficient to utilize the individual measured values within 30 s of the TCA. The time interval between the measured values must be chosen so that the shape of the curve is clearly defined, for example, at least in intervals of 5 s.

With this method and graphical evaluation methods an accuracy of $\pm 5 \times 10^{-9}$ Hz can be obtained if a Caesium type of reference oscillator, or better, is used.

Figure 6-3 shows the results of frequency determination performed in this manner.

Instead of time-consuming graphical evaluation methods, a software solution, which can directly process the single frequency measurement results of a frequency counter, would be best.

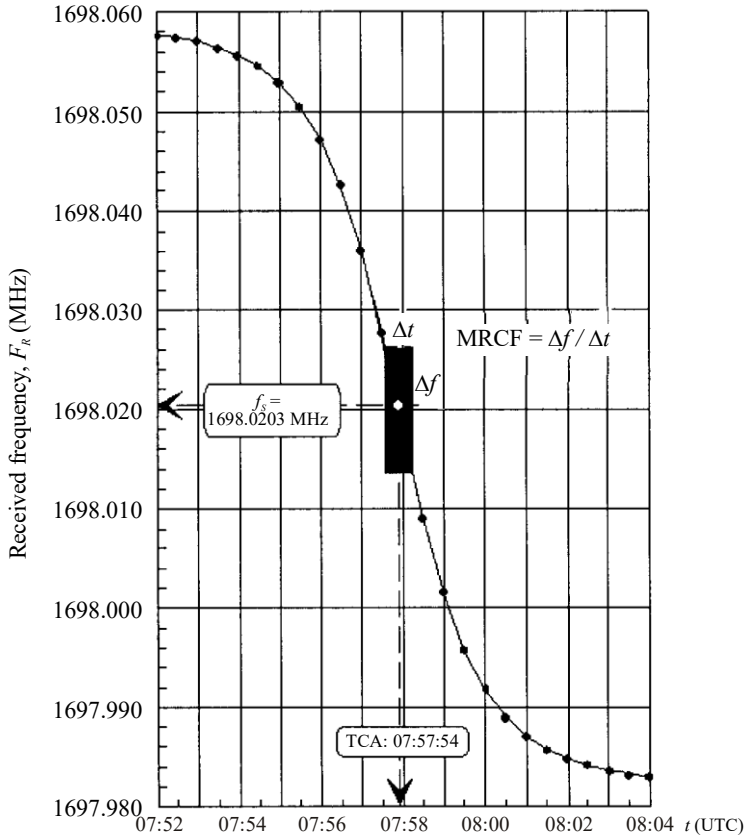
It is obvious that reliable frequency measurements can only be performed if the spectrum contains a characteristic frequency component to which the receiver can be synchronized. This, of course, also applies to the measurement of the frequencies of terrestrial stations.

6.1.2.3 Bandwidth measurements

For bandwidth measurements of GSO satellite emissions the same methods can be applied, in principle, as for measurements of terrestrial emissions. A description of these methods may be found in § 5.5.

FIGURE 6-2

Calculation of satellite frequency from Doppler-curve



Spectrum-5.1-02

In cases where there is a relative velocity between the space station and the monitoring station, the apparent transmitted bandwidth as measured at the monitoring station varies because of the Doppler shift effect in the same manner as described for the carrier frequency.

Two factors have to be taken into consideration:

– the entire frequency spectrum drifts during the time necessary for the bandwidth measurement;

– the frequency shift is slightly greater for signal components near the upper edge of the spectrum of the emission than for those near the lower edge. This difference could amount to hundreds of hertz for wide bandwidths. The effect causes the apparent bandwidth, as observed at the monitoring station, to vary slightly.

Automatic frequency control at the monitoring receiver can compensate for Doppler frequency shift of an emission. In this case, the normal measuring methods used to determine the bandwidth at terrestrial monitoring stations can be applied without radical changes.

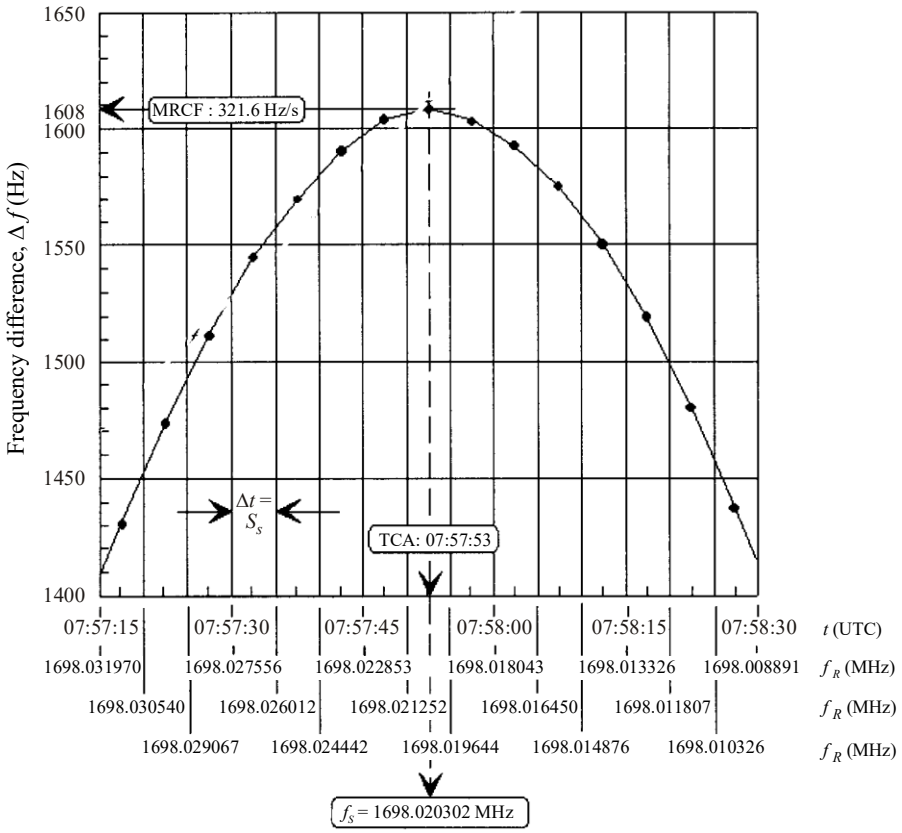
If the received signal is very weak, it is possible to ensure automatic correction of the receiver oscillator's frequency by using, as a reference signal, a carrier or pilot frequency emitted by the space station which is filtered by an extremely narrow bandpass filter.

If the monitoring station for space services does not possess appropriate receivers with automatic frequency control, account must be taken of the frequency shift of the space station during the measurement, if necessary, by making a simultaneous Doppler frequency measurement when determining the bandwidth.

It may also be necessary to make a simultaneous recording of the pfd so that the effect of pfd variations occurring during the analysis of the spectrum may be eliminated from the calculations.

FIGURE 6-3

Calculation of satellite frequency by differentiation of the Doppler-curve



6.1.2.4 Power flux-density measurements

6.1.2.4.1 Measurements in a reference bandwidth

The coordination and successful operation of space stations require that given maximum values of pfd be not exceeded on the surface of the Earth by emissions from a space station, including emissions from a reflecting satellite.

The values for individual frequency bands, space services, angles of arrival, and sharing conditions are given in RR Article **21**, Section V which should be available at the space monitoring facility. The limits to the epfd, produced at any point in the geostationary-satellite orbit by emissions from all the earth stations in a non-geostationary-satellite system in the fixed-satellite service in certain frequency bands are listed in Tables **22-1A**, **22-1B**, **22-1C**, **22-1D**, **22-1E**, **22-2** and **22-3** of Article **22** of the RR. The pfd in dB(W/m^2) is related to a particular bandwidth, in general to 4 kHz, 1 MHz, or 1.5 MHz, depending on the frequency of the fundamental emission.

The indication of the reference bandwidth (RefBW) is essential because the radiated power is normally not concentrated at a single frequency but is distributed within a band of frequencies.

6.1.2.4.2 Measurement of total pfd

In this case, the pfd is fully determined on the basis of the bandwidth occupied by an emission.

The bandwidth of the measurement filter should be selected accordingly. Such measurements are significant if, for example, the e.i.r.p. of a space station is to be calculated.

For frequency bands below 13 GHz, and provided that clear-sky conditions prevail, the total atmospheric loss may be taken as 0.1-0.2 dB for the calculations.

6.1.2.4.3 Measurement procedure

Whether the pfd in the reference bandwidth or the total pfd is to be measured, it is preferable to determine the pfd by a direct power measurement, especially at frequencies above about 1 GHz.

When this method is used, the pfd can be determined by equations (6-3a) and (6-3b):

$$PFD_{\mathrm{RefBW}} = P_{\mathrm{SYS}} - 30 - Ae - K_{\mathrm{BW}} + K_{\mathrm{POL}} \tag{6-3a}$$

$$pfd_{TOT} = P_{\mathrm{SYS}} - 30 - Ae + K_{\mathrm{POL}} \tag{6-3b}$$

where:

pfd_{RefBW} : pfd in reference bandwidth (RefBW) (dB(W/m^2))

pfd_{TOT} : pfd in bandwidth occupied by emission (dB(W/m^2))

P_{SYS} : system input power (see Note 1) (dBm)

30 : factor for converting dBm to dBW

A_e : effective antenna area (see Note 2) (dBm^2)

K_{BW} : correction factor for measuring bandwidth (see Note 3) (dB)

K_{POL} : polarization correction factor (see Note 4) (dB).

The pfd value derived from equations (6-3a) and (6-3b) may be used to calculate the e.i.r.p. of the space station by using equation (6-4). Knowledge of the slant range to the object at the time of measurement is required for the calculation.

$$e.i.r.p. = pfd + 10\log(4\pi d^2) + L_{ATM} \tag{6-4}$$

where:

e.i.r.p. : equivalent isotropically radiated power of space station (dBW)

pfd : measured pfd (dB(W/m^2))

d : distance between space station and receiving station (m)

L_{ATM} : atmospheric loss relative to free space (dB).

NOTE 1 – Input power is measured with a thermal power meter, normally connected to the IF output of the receiver and preceded by a bandpass filter of known effective bandwidth (r.m.s. measurement). The input signal is then substituted by a signal from a calibrated signal generator. Compensation for a possible Doppler shift of the incoming satellite signal should precede the IF output.

NOTE 2 – Effective antenna area (A_e) can be calculated from antenna aperture or gain by using equation (6-5):

$$A_e = 10\log(A\eta) = 10\log\left(\frac{\lambda^2}{4\pi}\right) + G_i \tag{6-5}$$

where:

A_e : effective antenna area (dBm^2)

A : antenna aperture (m^2)

η : efficiency expressed as a decimal

λ : wavelength (m)

G_i : isotropic antenna gain (dBi).

NOTE 3 – The bandwidth used for the measurement can be larger than the reference bandwidth, as long as the power is uniformly distributed in the measurement bandwidth. This condition can be checked by spectrum analysis. The measurement bandwidth is the effective bandwidth of the filter, which does not necessarily correspond to its 3 dB or 6 dB bandwidth. The correction factor is calculated by equation (6-6):

$$K_{BW} = 10 \log \left(\frac{B_M}{RefBW} \right) \tag{6-6}$$

where:

K_{BW} : bandwidth correction factor (dB)

B_M : measurement bandwidth

$RefBW$: reference bandwidth with same units as B_M.

NOTE 4 – In the case of matched polarization between the receiving antenna and the received signal, the polarization correction factor, K_{POL} = 0 dB. For linearly polarized reception of a circularly (right-hand or left-hand circular) polarized emission or vice versa, K_{POL} = 3 dB.

Since the pfd normally varies not only with frequency but also with time, its maximum value has to be determined. This can be done by recording the output signal of the power meter over a period of time at the frequency of interest. The time constant of the power sensor used will determine the rate of power variation that can be detected. Additional information on the e.i.r.p. calculation may be found in the existing monitoring Handbook.

The epfd is defined as the sum of the power flux-densities produced at a geostationary-satellite system receive station on the Earth's surface or in the geostationary orbit, as appropriate, by all the transmit stations within a non-geostationary-satellite system, taking into account the off-axis discrimination of a reference receiving antenna assumed to be pointing in its nominal direction. The formula used to calculate epfd is given in RR No. **22.5C.1**.

6.1.2.4.4 Measurement uncertainty

The degree of uncertainty for pfd measurements is essentially influenced by three factors:

– antenna gain uncertainty of the receiving antenna;

– uncertainty of the reference signal (power reference generator) for calibrating the measuring receiver/spectrum analyser;

– precision of antenna pointing/tracking.

Whereas the uncertainty of the reference source may, to a large extent, be controlled and minimized, the actual problem lies in the exact calibration of the antenna gain of the receiving antenna. Larger parabolic reflector systems may only be calibrated after assembly at the place of installation. Accordingly, satisfactory calculation of the antenna gain must account for the specific conditions at the installation site. [Newell *et al.*, 1986]; [Newell *et al.*, 1973]; [Satoh and Ogawa, 1982].

The expanded measurement uncertainty (coverage factor 2) should not exceed 2 dB. A reduction in the measurement uncertainty in all frequency bands should be sought.

The software algorithm, which is designed for its application by the BR to conduct examination of the non-GSO FSS system notifications for their compliance with limits contained in Tables **22-1A**, **22-1B**, **22-1C**, **22-1D**, **22-1E**, **22-2** and **22-3** of Article **22** of the RR, is described in Recommendation ITU-R S.1503.

6.1.2.4.5 Non-GSO constellation satellite pfd measurements

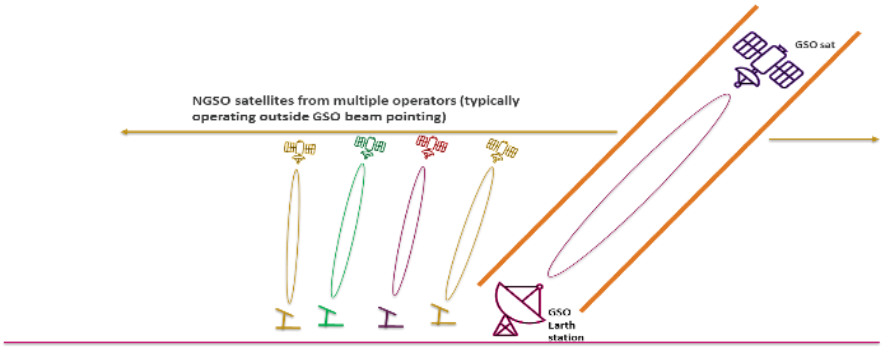
This section outlines special considerations for pfd measurements relating to non-GSO constellations which can be post processed if required. The most important requirement is a method for the initial pfd measurements.

Background

There is an increase in non-GSO constellations seeking access to Ku and Ka band spectrum. Multiple non-GSO systems operate using the same frequency as used by GSO systems, and in some cases terrestrial services, and ensure coexistence through beam separation, creating a complex sharing environment.

FIGURE 6-4

Non-GSO/GSO beam separation (GSO arc avoidance)



Type of interference scenarios (non-GSO-GSO)

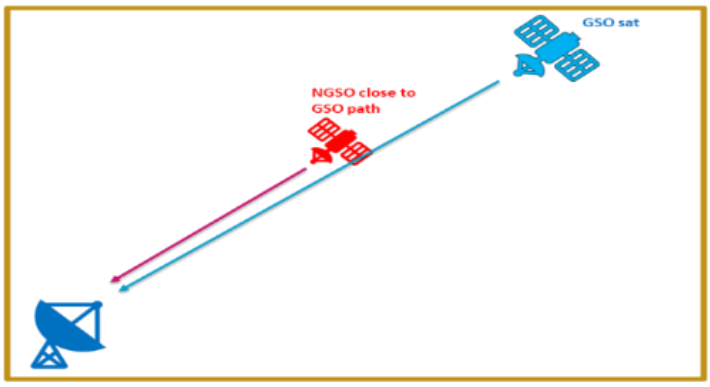
There are two types of interference scenarios:

a) Single satellite (in-line event[1])

A single non-GSO satellite can cause interference to a GSO satellite network earth station as the single non-GSO satellite passes through the GSO path (in-line event).

FIGURE 6-5

Interference scenario: Single satellite



b) Aggregate interference

Aggregate interference scenario is where interference contributions from multiple non-GSO satellites arrive through the side lobe of a GSO antenna (see diagram below).

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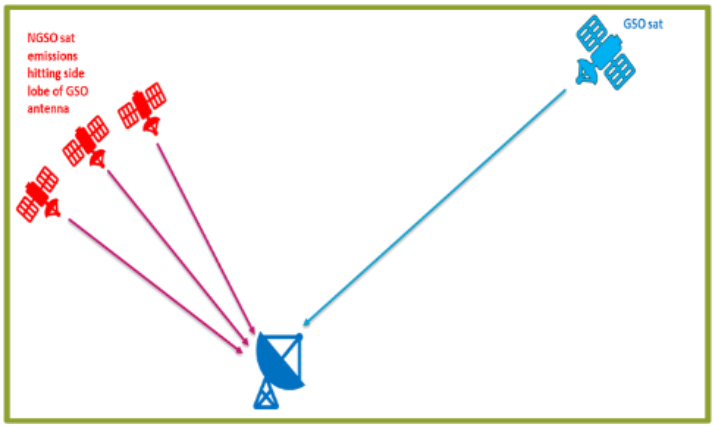
1 Momentary aligning of beams from different satellite operators.

FIGURE 6-6

Interference scenario: Aggregate interference



Methodology for single satellite interference assessment

A single non-GSO satellite can cause interference to a GSO satellite as it passes through the GSO path i.e. due to transmissions whilst the satellites are in-line.

Measurement of non-GSO emissions into GSO paths is impossible due to the presence of very strong GSO signals. However, one possible method is to measure the non-GSO satellite signal with a small offset from the GSO beam and will provide useful information in identifying the interfering satellite and this method can use victim antenna/site and require satellite ephemeris data.

Methodology for aggregate interference assessment

For assessment of aggregate interference from non-GSO will involve accurate pfd measurements of all non-GSO satellites in the visibility GSO earth station which provide important data for calculation of aggregate interference level, based on measured pfds.

Special consideration is needed in determining the size of the large parabolic dish needed for pfd measurements and higher density networks with more closely spaced satellites, will require a large dish to avoid overestimating non-GSO satellites pfds.

Use of flat panel antenna (FPA) for active/non active satellite measurement

Flat panel antennas can play an important role in determining active and non-active configurations in a network of interest, as the FPA can monitor multiple satellites simultaneously or quasi-simultaneously, and this value is required in the calculation of aggregate interference assessment.

6.1.2.5 Polarization measurements

Knowledge of the polarization of the satellite signal is essential because the determination of this basic signal characteristic can assist in the identification of unknown emissions. Consequently, a competent antenna system should be capable of distinguishing between different types of polarization.

The technical implementation of polarization measurements has to take into account the widespread use of the dual polarization technique in the frequency bands above 1 GHz which are used by the fixed-satellite service and the broadcasting-satellite service.

To obtain optimized receiving and measurement conditions for the satellite signal in terms of:

– maximum C/N;

– maximum C/I by sufficient polarization discrimination between orthogonally polarized signals.

It should be possible to match the polarization of the receiving antenna at the monitoring station to that of the incoming signal. In the case of dual linear polarization, full steerability of the polarization plane is required. A polarization discrimination of at least 20 dB should be provided.

6.1.2.6 Determination of orbital positions and orbital elements

The determination of orbital positions concerns GSO satellites and the determination of orbital elements concerns non-GSO satellites.

6.1.2.6.1 GSO satellites

A GSO satellite is subject to disturbances which tend to change its position in orbit. These disturbances lead to spurious orbital plane rotation and semi-major axis and eccentricity errors. This resulted in the fact that, as viewed by an observer on Earth, the satellite displays an oscillatory movement with a period of 24 h. This motion (the so-called "figure of eight") is composed of a North-South component and an in-plane component.

Space stations on board GSO satellites using frequencies allocated to the fixed-satellite or broadcasting-satellite service have to be kept within ± 0.1° of the longitude of their nominal position (see RR Article **22**, Section III), except for experimental stations on board GSO satellites which should be kept within ±0.5° longitude, and for the broadcasting-satellite service stations operating in the band 11.7-12.75 GHz which should be kept within the limits specified in RR Appendix **30**. Space stations need not comply with these limits as long as the satellite network does not cause unacceptable interference to any other satellite network whose space station complies with these limits. Position determination of GSO satellites is therefore a required task of a monitoring station for space services. The orbital position is usually computed from angle measurements in the azimuth and elevation planes of the receiving antenna. Section 6.1.7.4 illustrates one example of such a measurement.

6.1.2.6.2 Non-GSO satellites

The calculation of orbital elements of a non-GSO satellite (ephemeris data) from measurements of sufficient accuracy is a basic requirement for the:

– identification of an unknown space station (see § 6.1.5);

– investigation of possible reception times;

– predetermination of azimuth and elevation as a function of time, e.g. for computer-controlled antenna steering in cases where officially published data is not available.

A monitoring station for space services making use of passive mode measurements can provide the following timed measurement data:

– azimuth;

– elevation;

– Doppler shift.

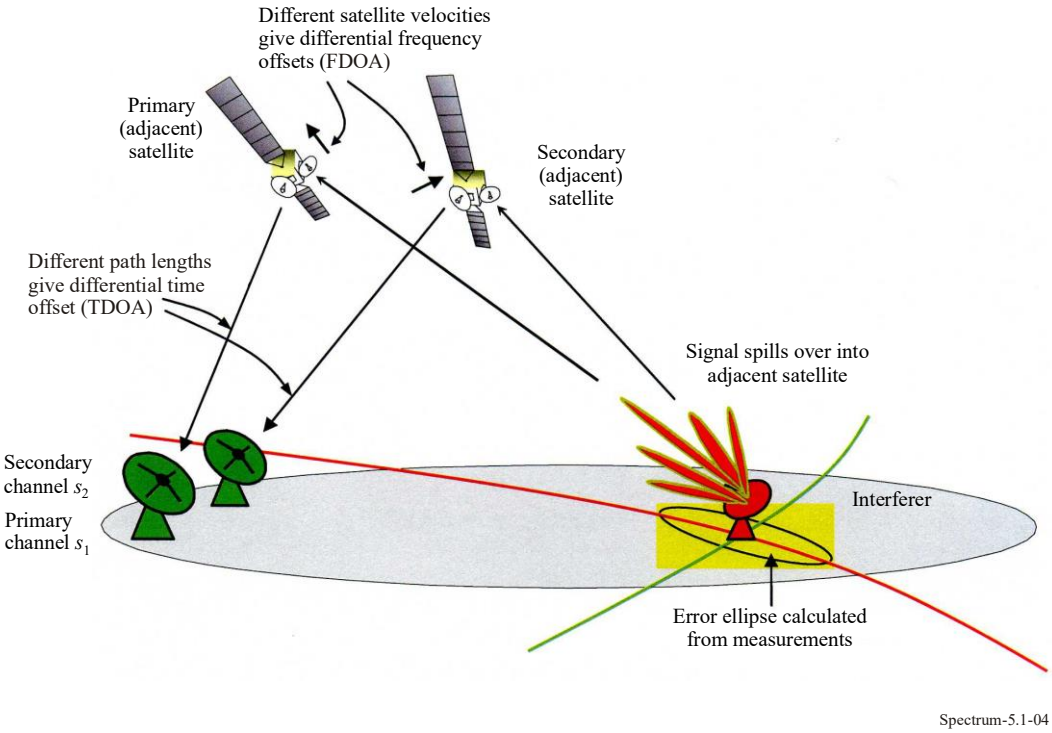
Since orbit determination requires the solving for at least six (e.g. Keplerian orbital elements), multiple measurements of the above-mentioned quantities are necessary. Typically, orbit determinations are the result of a statistical procedure in which the greater the volume of input data leads to improved accuracy of the orbital elements. When monitoring higher frequencies, i.e. above 1 GHz, methods based on the evaluation of angle measurements in the azimuth and elevation planes are preferred due to the narrower beamwidth of the receiving antenna at these frequencies.

6.1.2.7 Geolocation of transmitters on Earth using time and frequency difference measurements from two GSO satellites

Sources of interference located on Earth can affect the uplink signal received at the satellite. The receiver of the wanted signal perceives the interference as an interference of the downlink. Geolocation of radio transmitters affecting communication satellites in GSO orbit is a challenging task which is usually accomplished through analysis of time difference of arrival (TDOA) and frequency difference of arrival (FDOA) compound measurements. Both of these measurement types require that the transmissions be monitored through a second GSO satellite that lies within the transmitter beam. The GSO satellite carrying the unknown signal is usually referred to as the "primary satellite" and the above-mentioned second GSO satellite as "adjacent satellite". A TDOA measurement yields the difference in the time the same signal arrives at one ground-based receiver through the primary satellite and another ground-based receiver through the adjacent satellite. An FDOA measurement yields the difference in frequency measured between the signal which separately arrives at the two receivers. Usually, the two receivers are co-located at the same geographic site, but this is not a requirement (see Fig. 6-7). In "distributed mode", the two receivers used for geolocation are separated from one another, but are constrained to be within the downlink beam of each space station, respectively. Distributed mode must be used when the downlink footprints are non-intersecting; indeed, these downlinks may be received on different continents. When operating in distributed mode, the raw signal measurements must be transferred to a common location for further geolocation processing.

FIGURE 6-7

Geolocation of transmitters on Earth using TDOA and FDOA from two GSO satellites



The arrival time varies because the transmitted signal travels different distances as it passes through the two different satellites to each receiver. The received frequency differs because, generally, there is relative motion between the two satellites causing different Doppler frequency shifts on the transmissions. Although the positions of GSO satellites are loosely described as being fixed at specific positions over the Earth's equator, they actually do move about these nominal positions within certain limits. It is these movements that induce a measurable Doppler shift in the received signals. The received frequencies can also differ as the result of drifts in the oscillators which set the retransmission frequency on the downlink of each satellite.

Single TDOA or FDOA measurements combined with the satellite and ground station configuration each describe different surfaces on which the unknown transmitter must be located. The figure of the Earth (where nearly all transmitters of interest occur) provides a third surface that constrains the unknown's location. The intersection of these three surfaces provides an estimate of the unknown signal from a single pair of TDOA and FDOA measurements. Since measurement or modelling errors can lead to errors in the geolocation, additional TDOA and FDOA measurements combined in a statistical solution can serve to reduce such errors.

6.1.2.7.1 Measuring time and frequency differences

The two time series of the transmitter signal downlinked from each of the two GSO satellites are recorded and analysed to obtain time and frequency differences between them (i.e. TDOA and FDOA). This is done through the calculation of the cross ambiguity function (CAF) or correlation map in two dimensions. The value of CAF for a given time and frequency difference is the cross-correlation of the two recorded signals. In the special case of continuous wave (CW) emitters, no TDOA measurement can be generated since the two signals correlate for all delay time differences.

The CAF can be visualized in three dimensions where the value of the CAF is a function of both TDOA and FDOA. For the case of a single interference signal in the selected frequency range, the maximum value of CAF with respect to TDOA and FDOA selects those shifts as the TDOA and FDOA values that are presented to the geolocation algorithm that calculates the location of a single transmitter. For a CW emitter, a ridge along a line of constant FDOA is the result. Alternatively, several broadband transmitters from multiple locations will produce multiple CAF peaks. A detailed discussion of algorithms used to calculate and analyse the CAF is given by Stein [1981].

6.1.2.7.2 Geolocation algorithm

The geolocation algorithm often uses TDOA and/or FDOA measurements in an iterative least squares procedure to estimate the location where the transmitted signal originates. In its simplest form, an initial guess of the transmitter location and the given orbits of the two satellites are combined with the physical laws of satellite motion to generate predicted TDOA and FDOA measurements. The difference between the actual and predicted TDOA and FDOA measurement values (the residuals) are used to generate adjustments to the transmitter position. This adjusted transmitter location is used to generate a second set of predicted TDOA and FDOA measurements which imply further adjustments to the transmitter position and so forth. An iterative solution is required because the problem is inherently non-linear.

Iterations continue until the adjustments in the transmitter position are sufficiently small at which point the geolocation solution is said to have converged.

TDOA and FDOA measurements made over time converge on the transmitter location based on the laws of physics. Additional geolocation solutions are also available for other combinations of measurement types. For example, geolocations of CW emitters are possible from a series of FDOA measurements alone with reduced accuracy over what would have been available with the corresponding TDOA measurements that are accessible from a broadbanded signal. Alternatively, use of a third satellite to generate a second set of TDOA and/or FDOA measurements can also provide improved solutions, however, this comes at the expense of greater use of receiver antenna resources. TDOA-only solutions are possible by the use of a third satellite, but the surfaces of constant TDOA derived from the two satellite pairs are nearly parallel making their practical use more dependent on TDOA measurement precision or more time for gathering measurements.

In practice, the accuracy of the satellite ephemeris of each of the two satellites limits the accuracy of the geolocation solution. Improved geolocation performance is achieved through TDOA and FDOA measurements of separate transmitter signals, sometimes referred to as reference locators, which originate from known locations and pass through the same pair of satellites as the signal of interest. These reference locators are used to refine the orbital ephemeris of one or both of the satellites which, in turn, improves the accuracy of the estimate of the location of the transmitter of the signal of interest.

6.1.2.7.3 Uncertainty analysis

The goal of uncertainty analysis of a geolocation problem is to provide a realistic appraisal of the accuracy of a geolocation solution.

Providing accurate uncertainty analyses can sometimes be complex and difficult. The precision of the individual TDOA and FDOA measurements are both proportional to the square root of the signal-to-noise ratio obtained in the correlation solution. The precision of TDOA and FDOA measurements are also proportional to the signal bandwidth and measurement time, respectively. The least squares geolocation solution provides formal error estimates and confidence intervals of the location of the transmitter of interest that are based on the uncertainties assigned to the TDOA and FDOA measurements. The reliability of these TDOA and FDOA uncertainties can be checked statistically against their corresponding measurement residuals. Alternatively, if a sufficient number of TDOA and FDOA measurements are available, the uncertainties in the TDOA and FDOA measurements can be estimated by the same solutions procedure. An example error analysis is given by [Bardelli *et al.*, 1995].

Two caveats must also be given. First, the uncertainties in the TDOA and FDOA measurements may be large enough so as to invalidate the assumption that the solution is linear in the spanned region of parameter space.

This means that the formal errors generated by the geolocation algorithm that are based on linearized statistical analysis are less accurate. Monte Carlo techniques may be employed to generate better uncertainty estimates in these cases.

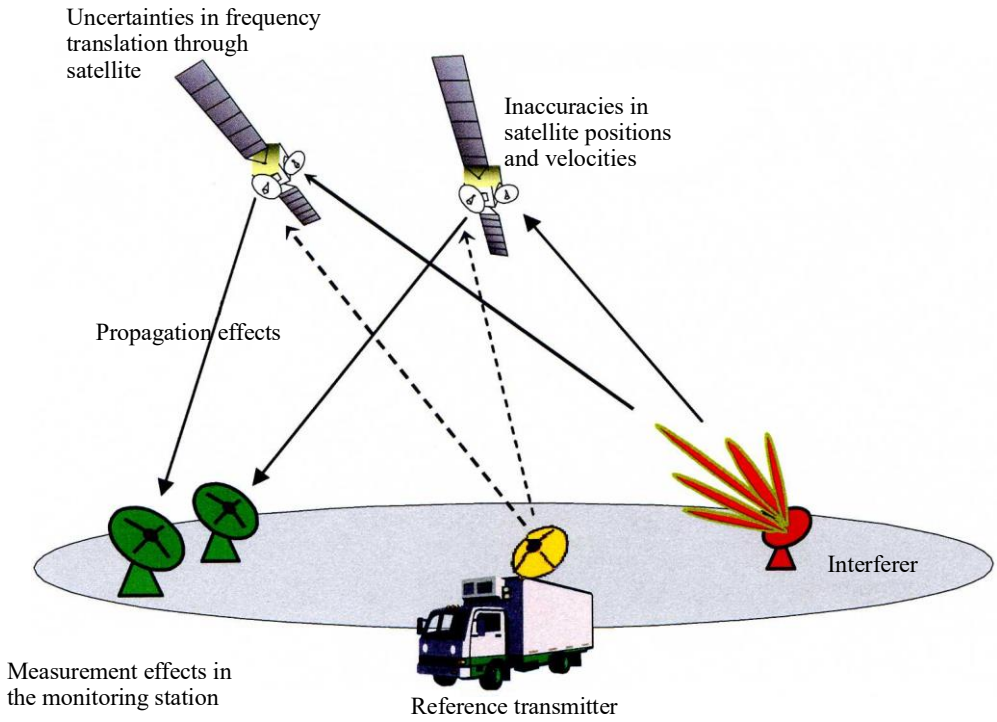
Second, the formal uncertainties account for random error and only partially for any systematic errors. Systematic errors can arise, for example, through incomplete modelling of the physics of the TDOA and FDOA measurements or in the force model used to produce the satellite ephemeris.

The impact of systematic errors can be assessed by very thorough simulation of the geolocation technique and all of its systematic error sources.

There are several potential inaccuracies resulting in a location error. The error can be substantially reduced by using reference transmitters whose geographical coordinates are exactly known (see Fig. 6-8).

FIGURE 6-8

Geolocation of transmitters on Earth using TDOA and FDOA from two GSO satellites using a reference transmitter



Spectrum-5.1-05

Reference stations deployed over a huge area can eliminate errors due to ephemeris inaccuracies whereas the use of reference stations located in the vicinity of the interferer can minimize the location error. See §§ 6.1.5.4.5 and 6.1.5.4.6.

6.1.2.8 Geolocation of transmitters on Earth using a single GSO satellite and inverse Doppler shift

The location of a transmitter (or interference) on the surface of the Earth may be determined under certain conditions using the transmitted signals relayed through a single GSO communications satellite. The small Doppler shift on the signal carrier frequency, which is induced by the slight motion of the satellite relative to the Earth during an orbit can be exploited to estimate the location of the transmitter to the point (within tens of km) that mobile units may be deployed to pinpoint transmitter or interference location. The technique utilizes measurements of the carrier frequency of infrequent, short transmissions distributed over several hours. Super resolution techniques and signal processing are used to estimate the small Doppler shift in the transmitted signals with the needed degree of accuracy. Predictions of the position and velocity of a satellite can be refined using a reference transmitter [Koets, Bentley, 1999].

Non-zero inclination and eccentricity of a GSO orbit induces some motion in the satellite relative to the surface of the Earth. This motion induces a small Doppler shift, which can be exploited to estimate the location of the transmitter. The technique even makes use of observations of infrequent and short transmissions scattered over a period of several hours. The carrier frequencies of the transmissions must be measured with very high precision in order to use this method. A non-linear iterative estimation technique is then applied. See § 6.1.2.8.3 and Fig. 6-9 for discussion of GSO satellite excursions.

For all these reasons the implementation of the geolocation method using one satellite is very difficult. Moreover, it imposes assumptions on the transmitter itself that are generally not met, such as:

– an ultra stable local oscillator of the transmitter during a long period of time;

– an emission of the transmitter during a long period of time.

6.1.2.8.1 Geolocation algorithm

The geolocation algorithm utilizes a mathematical expression (f_R) to predict the carrier frequency of a signal that is relayed through a GSO satellite. The expression incorporates the known position and velocity of the satellite and the location of the receiver, as well as the unknown location of the sought transmitter. The effects of uplink Doppler shift, frequency translation within the satellite transponder, and downlink Doppler shift must be taken into account.

All vector quantities are expressed in the three-dimensional Earth-centred Earth-fixed Cartesian coordinate system:

$$f_R = \left[f_T \cdot \left(1 + \frac{\vec{v}_S \cdot (\vec{r} - \vec{r}_S)}{c \cdot \|\vec{r} - \vec{r}_S\|}\right) + \Delta_f\right] \cdot \left(1 + \frac{v_D}{c}\right) \tag{6-7}$$

where:

f_R : carrier frequency of the received signal

f_T : carrier frequency of the transmitted signal

v_S : velocity vector of the satellite at the observation time

r_S : position vector of the satellite at the observation time

r : position vector of the transmitter

Δ_f : frequency translation in the satellite transponder

v_D : scalar range rate between the satellite and the receiver

c : propagation velocity of the signal.

Equation (6-7) is a function of known and unknown parameters. The known parameters consist of the position and velocity of the satellite, frequency translation, and the range rate between the satellite and receiver. The satellite position and velocity and range rate are dependent on time. The unknown parameter set consists of the location and carrier frequency of the transmitter. Measurements of the actual carrier frequency of the signal at the receiver are made at several observation times. The geolocation algorithm estimates a set of unknown parameters such that the sum of square errors between the measured carrier frequency and the carrier frequency predicted from the expression is a minimum.

The geolocation algorithm uses a linearized version of the received frequency expression, which is a first order multi-dimensional Taylor series expansion of equation (6-7). A set of linear equations can be formed using this expression and assembled as the matrix equation:

$$E = A\Delta \tag{6-8}$$

where E is the column vector of measurements of the carrier frequency of the received signal at each of the observation times, and $A = [A_f A_x A_y A_Z]$ where each column vector A_i is the derivative of the expression with respect to the parameter i, computed at each observation time, and Δ is the vector of errors between the true parameter values and their initial estimates. The matrix equation is solved for the vector Δ in a linear least squares sense and this error vector is used to iterate and refine the initial parameter estimates. Since the linear equation used is only an approximation to the model, several iterations of the process are performed, using the most recently obtained parameter estimates for each step. The parameter values converge to the final frequency and location estimates.

6.1.2.8.2 Frequency (Doppler) measurement

Since a GSO satellite moves slowly relative to a fixed point of the Earth, the Doppler shifts observed in a communications link are small, on the order of tens of Hertz. Accurate geolocation is therefore dependent on very accurate carrier frequency estimation (rubidium standard is sufficient).

The multiple signal classification (MUSIC) algorithm may be used for frequency estimation. The resolution of the frequency estimator is limited only by machine precision and not by the length of the data set. The accuracy of the estimates is constrained by the signal-to-noise ratio. The MUSIC algorithm produces a much more precise frequency estimate than fast-Fourier-transform-based algorithms.

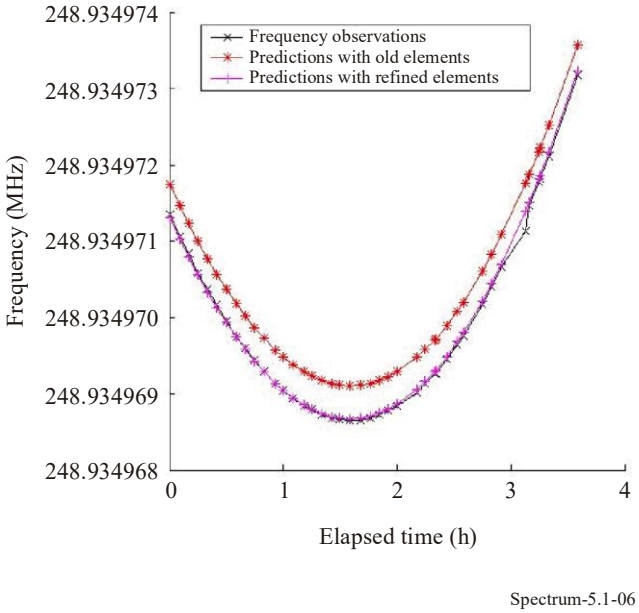
6.1.2.8.3 Position and velocity correction

Accurate geolocation results are dependent upon accurate knowledge of the position and velocity vectors of the satellite at every time of observation. These vectors are typically computed using an orbit propagation model and a set of six orbital elements that describe the orbit of the satellite. These elements are periodically updated based on observations of the satellite and the updated element sets available. Orbit propagation algorithms model the gravitational effects of the Earth, sun, and moon to predict the position and velocity of the satellite for times later than the time at which the elements are computed. There are forces that affect the motion of a satellite that are not modelled. Therefore, the resulting position and velocity estimates become less accurate as the time difference between the prediction time and the time the element set was updated becomes large. The frequency translation within the satellite transponder is also imperfectly known.

It is necessary to refine the satellite position and velocity predictions and the translation frequency to improve the accuracy of location estimates. A reference transmitter at a known location and with a known carrier frequency can be used to refine these values. The reference transmitter should relay signals through the satellite during the same period that signals of interest are observed. The carrier frequency of each of the reference signals observed at the receiver is computed in the same manner as a target signal. These observed reference frequencies are then compared to frequencies that are predicted by evaluating the expression with the known location of the reference transmitter and initial estimates of the set of orbital elements and the translation frequency to refine the results. Figure 6-9 illustrates the improvement in frequency predictions obtained with the refined orbital elements and the refined translation frequency.

FIGURE 6-9

Improved frequency predictions with orbital element refinement

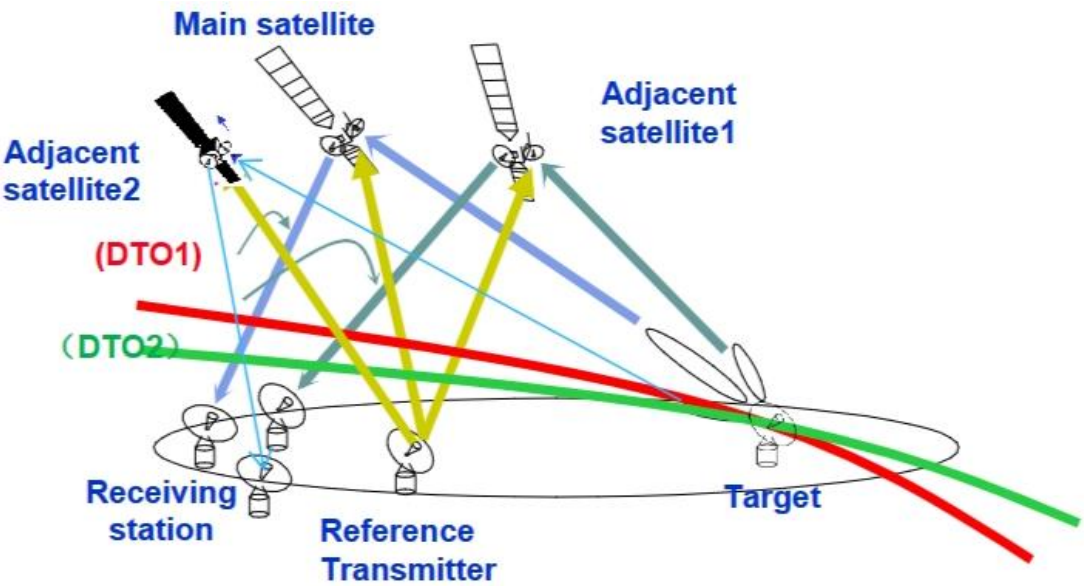


6.1.2.9 Geolocation of transmitters on Earth using time difference measurements from three GSO satellites

As indicated in Report ITU-R SM.2424, one limitation of the geolocation method based on TDOA and FDOA with two GSO satellites is the uncertainty of the FDOA which can fluctuate up and down especially in the case of imprecise ephemeris or insufficient number of reference stations. This fluctuation could result in poor accuracy. In this case, a geolocation method using two TDOA measurements with three satellites is provided to achieve higher accuracy. The concept of this method is shown in Fig. 6-10.

FIGURE 6-10

Geolocation of transmitters on Earth using TDOA and TDOA from three GSO satellites



The two TDOA measurements represent the time difference of the same signal arriving at one ground-based receiver through the primary satellite and another ground-based receiver through the adjacent satellite 1 or adjacent satellite 2 respectively. Each TDOA measurement is represented in the form of a hyperboloid surface, and the TDOA line is the result that the hyperboloid surface meets the earth surface. The intersection point of the two TDOA lines provides an estimate location of the unknown transmitter.

6.1.2.9.1 TDOA Measurement

Three ground-based receivers simultaneously record and analyse three time series of the same transmitter signal downlinked from one primary satellite and two adjacent satellites. TDOA values are obtained through the CAF, as same as § 6.1.2.7.1, while the FDOA value could be ignored. To obtain two TDOA measurements, two separate CAF calculations need to be performed using time series from the primary satellite and different adjacent satellites.

6.1.2.9.2 Uncertainty analysis

The accuracy of the geolocation method using two TDOA measurements from three GSO satellites mainly depends on several factors including longitude span between the two adjacent satellites, the precision of satellite ephemeris, the geographic position of the reference station, as well as signal acquisition bandwidth and time synchronization error of the system. Besides, the algorithms used to estimate accurate TDOA value and geolocation result are different by each manufacturer.

The longitude span between the two adjacent satellites is a key factor to geolocation accuracy. The greater the longitudinal span, the larger the angle between the two TDOA lines, and therefore the TDOA measurement shift caused by time synchronization would have a relatively smaller effect on the geolocation accuracy. On the contrary, if the two adjacent GSO satellites are too close to each other, the two TDOA lines would be almost parallel and overlap, and the TDOA measurements shift would lead to big deviations to the intersection points of the two TDOA lines, and thus bring a significantly decrease to the geolocation accuracy. There is another scenario the geolocation accuracy would decrease, is that when the interferer or the reference station is located near the equator of the Earth, the two TDOA lines would be both nearly perpendicular to the equator.

Nevertheless, if the adjacent satellite is too far from the primary satellite, the geolocation may result in failure because the adjacent satellite may be unable to receive the sidelobe of the reference signal or the interference.

6.1.2.10 Frequency occupancy measurements and GSO orbit position occupancy measurements

Preparations in the planning of new satellite systems should include specific investigations into the occupancy of the downlink frequencies by other satellite systems. This applies in general, since it cannot always be assumed that utilization of frequencies has been subject to coordination or notification. Such occupancy measurements are therefore valuable in order to avoid unexpected interference.

Automatic radio frequency spectrum recording equipment has proved to be very useful for monitoring low orbiting satellite emissions. Using non-directional or hemispheric-shaped beam antennas, the results obtained over a period of several days permit the determination of the occupancy of the frequency band by satellite emissions. In addition, the approximate determination of the satellite frequencies is possible, as are the expected times of reception and the computation of the period of revolution with a good degree of accuracy. One example of a frequency spectrum record is given in § 6.1.7.1.

General frequency occupancy monitoring methods using low-gain antennas are as a rule, not suitable for frequency bands above about 3 GHz. For low pfd signals, directional antennas with adequate antenna gain are required. In the case of GSO space stations, however, occupancy measurements are possible which:

– determine the positions occupied by space stations;

– provide frequency and time-related data regarding the occupancy of frequency bands at occupied positions.

In order to identify occupied positions, an inter-active process is recommended to steer the directional antenna used for reception along the GSO orbit within its half-power beamwidth, during which measurements are continuously taken from the analyser used for the signal processing to monitor crossing of the threshold values. After scanning the orbit segment visible to the radio monitoring station, the analyser is switched to the next frequency sub-band and the whole process is repeated.

The time and frequency-related occupancy measurements for a pre-determined position allow for variations, which should be coordinated precisely with the target selected. One example is illustrated in § 6.1.7.3.

6.1.2.11 Measurements below the noise floor

Often there is a need to analyse weak radio signals or parts of signals which are hidden below the noise floor. Especially space radio emissions suffer from this situation. Recommendation ITU-R SM.1681, was developed to solve this problem. Figure 6-11 shows the typical block diagram for such measurements.

The measurement of low-level emissions below the noise floor is based on an integration method which subtracts the noise spectrum from the signal.

The IF signal is sampled by an analogue/digital converter and stored on a hard disc. This measurement is repeated typically 10 000 times in order to acquire 10 000 recorded samples. Immediately thereafter the antenna is pointed to an adjacent orbit position with the satellite outside the antenna beam thus receiving the noise only under the same environmental conditions.

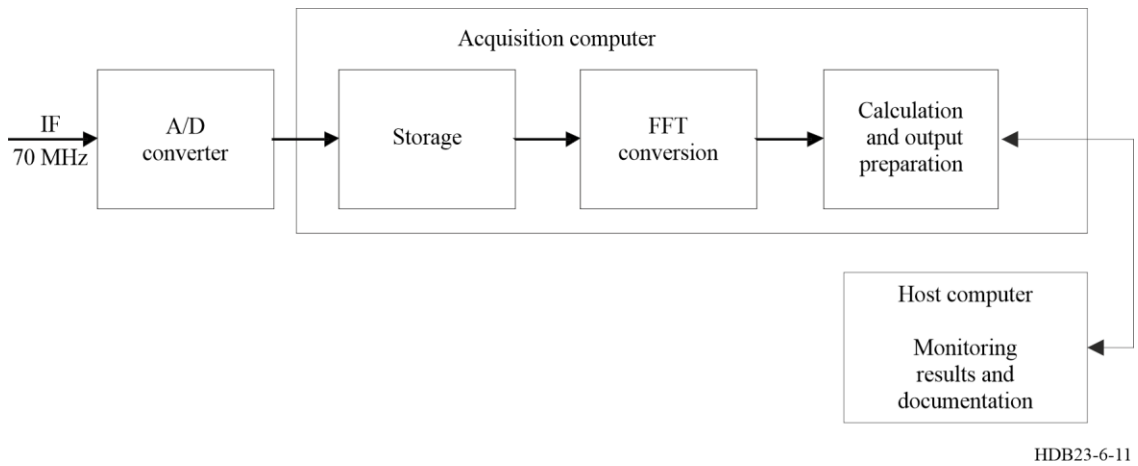
Another 10 000 samples are taken and stored on the hard disk. Both 10 000 sample lines are linearly averaged and subtracted from each other. This results in a noise reduction of typically 10 to 20 dB.

It should be noted that an excellent frequency stability of the whole receiving path is necessary.

Also, any noticeable satellite Doppler frequency shift must be eliminated or deducted.

FIGURE 6-11

Block diagram for monitoring below the noise floor



6.1.3 Equipment and facility requirements

The purpose of the following paragraphs is to highlight some system characteristics.

Further details regarding figure of merit, antenna systems, antenna steering and auto-tracking are contained in the Handbook on Satellite communications (FSS), and in the publications listed in the Bibliography.

6.1.3.1 General

The technical concept of a radio monitoring station for space services is essentially determined by the tasks to be performed in accordance with the specific needs of the administration.

New developments in the field of space services should be taken into consideration during the planning of the concept. Some important aspects are listed in Table 6-2.

The required measurement accuracies, e.g. for frequency and pfd measurements and in particular for angle measurements for the determination of the position of GSO space stations or the orbital elements of non-GSO satellites, are of special importance.

In general, as in more conventional monitoring stations, equipment for monitoring signals from space stations must have adequate flexibility to tune over a wide range of frequencies, in contrast to the spot frequency coverage that suffices for the needs of a research or operational space agency.

TABLE 6-2

Tasks and their sphere of influence with respect to the technical concept of the monitoring station for space services

No.	Tasks	Sphere of influence
1	Which part of the frequency spectrum should be able to be monitored?	Number and kind of antenna systems
2	Which satellite systems should be included in the monitoring? Which power flux-densities do these systems produce at the locality of reception? What carrier-to-noise ratio should be achieved?	Figure of merit of the receiving system (antenna gain, system noise temperature)
3	Should position determination of GSO satellites be possible?	Pointing accuracy, kind of antenna steering, receiver concept
4	Should determination of orbital elements of non-GSO satellites be possible?	Pointing accuracy, kind of antenna steering, acceleration and antenna steering velocity, receiver concept
5	Should determination of polarization characteristics and measurements in case of dual polarization systems be possible?	Antenna feed system
6	Should geolocation of transmitters on Earth be possible?	Number and kind of antenna systems Set of receivers specially used for geolocation

6.1.3.2 Figure of merit of a space monitoring system

The achievable *C*/*N* on reception of an emission from space depends on the following factors:

– the pfd of the signal at the reception site;

– the gain of the receiving antenna;

– the system noise temperature of the receive system.

The figure of merit, *G*/*T*, of a receiving system is the ratio between the gain of the receiving antenna in the direction of the received signal and the receiving system noise temperature as set out in equation (6-9).

$$\frac{G}{T} = G - T_{RS} \tag{6-9}$$

$$\left(\frac{G}{T}\right) = \left(\frac{C}{N}\right) - pfd - 10\log\left(\frac{\lambda^2}{4\pi}\right) + 10\log(\mathrm{kB}) \tag{6-10}$$

where:

G/T : figure of merit (dB/K)

G : antenna gain (dBi)

T_{RS} : system noise temperature of receiving system (dB(K))

C/N : wanted carrier-to-noise ratio in measurement bandwidth, B (dB)

pfd : pfd in measurement bandwidth, *B* (dB(W/m^2))

$\lambda^2/4\pi$: effective area of an isotropic antenna (m^2)

k : Boltzmann's constant (1.38×10^{-23} J/K)

B : measurement bandwidth (Hz).

In the case of the fixed-satellite service, the link conditions for a planned system are known exactly. The required *G*/*T* for a given *C*/*N* can be calculated by using equation (6-10). The measurement bandwidth is equivalent to the receiving bandwidth. It is up to the system developer to decide whether a required *G*/*T* should be achieved by means of an increase in the antenna gain, or a reduction in the noise temperature.

Such clarity of conditions cannot be expected for the space monitoring activity. The method used is, however, similar. The desired *G*/*T* is calculated on the basis of the lowest pfd values of those space stations for which the technical analysis of their emission characteristics is regarded as necessary for the monitoring station.

Direct measurement of *G*/*T* of a space monitoring system is preferred to taking the ratio of separately measured *G* and *T*, because the opportunity for error is reduced. Separate measurements of *G* and *T* also require the use of a signal generator, which unnecessarily introduces an additional factor of uncertainty. The sun, rather than a radio star, is often used for *G*/*T* measurements for pfd calibration purposes at monitoring stations because of its much stronger signal. Should, however, the receiving system be sufficiently sensitive, use of radio stars would be better.

6.1.3.2.1 Terms defining *G*/*T*

The figure of merit is usually determined at 5° elevation and expressed in (dB/K) units i.e. *G*/*T* (dB/K) = 10 log (*G*/*T* numeric).

$$G/T \text{ (dB/K)} = \text{antenna gain (dBi)} - 10 \log (\text{system noise temperature (K)}) \tag{6-11}$$

or

$$G/T \text{ (numeric)} = \frac{8\pi k r_1 r_2 f^2 (y_{sun} - 1)}{s c^2 y_x} \tag{6-12}$$

where:

k : Boltzmann's constant (1.38×10^{-23} J/K)

r_1 : correction factor for atmospheric attenuation; for angles ≥ 5°

where:

$$r_1 = \text{antilog} \frac{\frac{A}{\sin\theta} \text{ (dB)}}{10} \tag{6-13}$$

A : the one-way atmospheric absorption in decibels for a vertical path and θ is the Sun's elevation angle at the time of measurement

r_2 : correction factor for receiving antenna half power beamwidth relative to the angular diameter of the Sun

where:

$$r_2 = 1 + \frac{401.4}{\vartheta_h^2} \quad \text{and} \quad \vartheta_h^2 \tag{6-14}$$

ϑ_h^2 : antenna half power beamwidth (min)

f : frequency (Hz)

y_{sun} : measured values, expressed in numeric units, where:

$$y_{sun} = \text{antilog} = \frac{Y_{sun}(\text{dB})}{10} \tag{6-15}$$

s : Sun flux-density obtained from a national standards laboratory; if the Sun flux-density, s, at the frequency (f) of direct interest is not available, the following interpolation equation should be used, instead of linear interpolation, to obtain greater accuracy:

$$s = \left(\frac{s_1}{s_2}\right)^{R_2} \tag{6-16}$$

where:

s_1 : flux at lower frequency (f_1), (J/m^2)

s_2 : flux at higher frequency (f_2), (J/m^2)

$$R_2 = \frac{\log(f/f_2)}{\log(f_1/f_2)} \tag{6-17}$$

c : velocity of light (3×10^8 m/s)

y_x : measured values, expressed in numeric units, where:

$$y_x = \text{antilog}\ \frac{Y_x(\text{dB})}{10} \tag{6-18}$$

6.1.3.2.2 *G*/*T* measurement procedures

A receiver of the type usually found at monitoring stations, having an IF output voltage indicator, e.g. voltmeter or oscilloscope, is required. It is highly desirable that the indicator has a voltage resolution of 0.1 dB (1%) or better. The receiver must be stable and have no significant gain changes during the measurement period.

For the measurements:

– the receiver automatic gain circuit should be switched off;

– the antenna should be pointed towards the Sun and maximum signal obtained. The Sun should have an elevation angle greater than about 30° to avoid atmospheric effects and to ensure that the correction factors r_1 and r_2 are minimally affected;

– the antenna should then be slewed, in azimuth only, away from the Sun, e.g. more than a few degrees. The IF voltage level should be noted. This voltage corresponds to the cold sky reference value;

– the antenna should then be returned in azimuth towards the sun and the voltage noted. The difference in readings equals Y_{sun} (dB);

– the antenna should then be slewed, in elevation coordinate only, down from the Sun to 5° elevation and the voltage noted. The difference between this voltage level and the cold sky level is Y_x (dB) for x° of elevation. It should be noted that 5° of elevation (x°) is a common reference standard.

The G/T can then be evaluated using the measured values of y_{sun} and y_x and applying the correction values r_1 and r_2. The Sun flux-density, s, can be obtained from a national standard laboratory.

Using the equation for G/T, the root-sum-square uncertainty of the measurement is of the order of < 0.5 dB.

It is necessary that the measurement procedures be carried out on a bright, sunny day.

6.1.3.3 Antenna systems

The monitoring antenna gain should be as high as possible in order to provide a good minimum sensitivity limit for the measuring equipment.

Helical antennas or dipole antenna arrays are suitable for the 100-1 000 MHz frequency range. As individual antennas, they provide a gain of about 12 to 16 dBi.

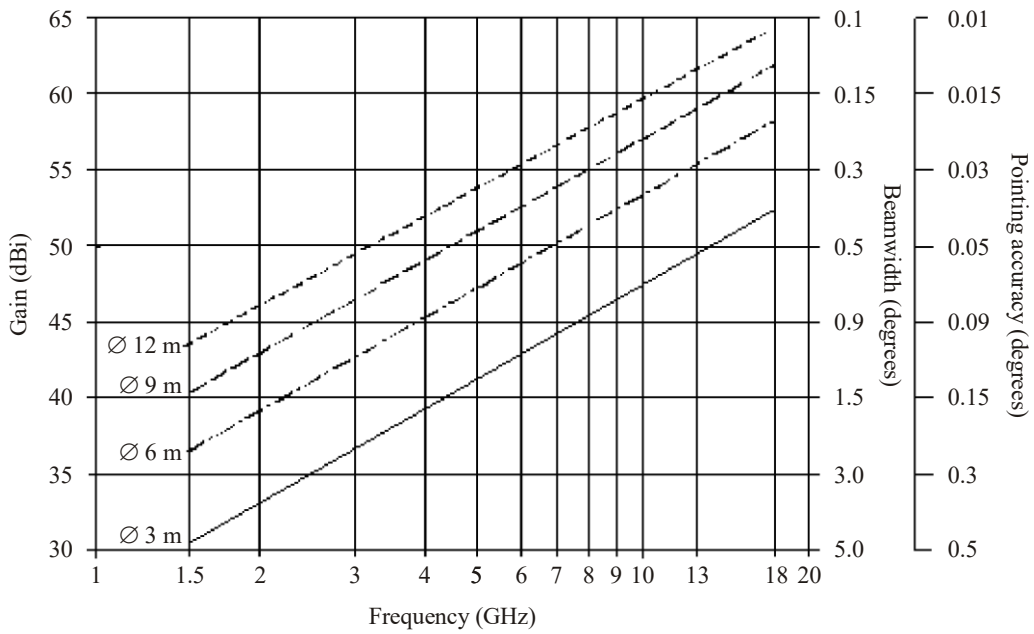
For the frequency range from 1 to 26.5 GHz, one parabolic reflector with one broadband feed at the prime focus is adequate. If optimised polarization and directivity characteristics are required, a design, which uses interchangeable feed system, is preferred. Examples for such technical solutions are given in § 6.1.6.1.

Figure 6-12 illustrates the antenna gain as a function of frequency for the different diameters of the parabolic reflector, assuming a typical antenna efficiency of 55%. The diameter of the reflector should be a minimum of 3 m. The antenna gain (in linear units) is raised as a square of the frequency (1/ƛ); see equation (6-5), and Recommendation ITU-R F.699 *recommends* 3) (i.e. $G_{max} \approx 20 \log \frac{D}{\lambda} + 7.7$).

In this case, antenna gains ranging from 31 dBi at 1.5 GHz to 53 dBi at 18 GHz may be obtained. Extrapolation to higher frequencies is applicable. Generally, antennas with a diameter ranging from 6 m to 12 m are used. Generally, the available bandwidth does not exceed 10 percent of the centre frequency.

FIGURE 6-12

Antenna gain, 3 dB beamwidth and pointing accuracy as a function of frequency for the different diameters of the parabolic reflector and an antenna efficiency of 55%



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In some cases, the use of log-periodic antennas may be of advantage. Antennas of this type provide good general coverage over a 10 to 1 frequency range and have been used for satellite monitoring on frequencies between 50 and 5 000 MHz. The disadvantage in this case is that the antenna gain is generally ranging below 10 dBi.

For tracking of the large scale non-GSO constellations that are generally operating in the frequency band above 1 GHz, the use of phased array antennas may be a beneficial supplement to the mechanical antennas. They can track multiple satellites with multiple beams simultaneously or quasi simultaneously. In addition, the high integration feature makes the phased array antennas easier to be portable. However, these antennas are more complex compared to parabolic antennas.

6.1.3.4 Antenna steering

The antenna drive system should allow either manual or computer-controlled adjustment. If accurate position determination of GSO satellites is required or if the calculation of orbital elements of a space station based on angle measurements is seen as a required task, then autotracking is necessary. Step-track or monopulse tracking are the two possible solutions.

The step-track technique is based on measurements of the strength of the received signal in positions around the expected satellite position. By computation the optimum is found stepwise. The monopulse technique is based on the analysis of the wave type arriving in the tracking receiver. Only when the antenna is pointed directly towards the satellite, the expected wave type (waveguide mode) is produced. Other wave types produce the tracking information for proper pointing. The monopulse tracking is usable for GSO and non-GSO satellites and have no impact on the power measurements.

6.1.3.5 Antenna beamwidth necessary for angle measurements

The intention in this sub-section is to establish a relationship between the half-power (3 dB) beamwidth of an antenna and the achievable pointing accuracy. This is of interest with respect to auto-tracking techniques in those cases where the monitoring of the station-keeping of GSO space stations or the calculation of the orbital elements of non-GSO satellites are seen as a required task of a radio monitoring station (see § 6.1.2.6).

Pointing accuracy is a measure of how well an antenna system determines the look angles (azimuth, elevation) of an object. In this respect there is a difference between space monitoring, and earth stations of the fixed-satellite service, since in the case of the latter, even a smallest possible relative alignment error (relative to the space station) is significant.

A relationship between the half-power beamwidth of an antenna and the maximum achievable pointing accuracy can be established:

$$R = n \cdot \theta_0 \tag{6-19}$$

where:

R : angle measurement error (degrees)

n : improvement factor

θ_0 : half-power beamwidth (degrees).

For optimised narrow-band antennas, $n = 0.01$. For a broadband antenna of the kind generally used by a radio monitoring station for space services, a factor of 0.1 seems to be realistic if a monopulse system is used and 0.15 if a step-track system is used. The remaining variable, the half-power beamwidth is a function of the diameter of the reflector.

The suitable half-power beamwidth should be selected by taking into account the smallest longitudinal position tolerance of ±0.1° as defined in the RR. A tolerance of ±0.1° of the longitude defines an angular segment of the equatorial orbital plane. In the restrictive case where a monitoring station is operated on the equator, position keeping would have to be checked by angle measurements in only the elevation plane of the antenna. When the monitoring station is shifted to the South or North, a rotation takes place in the azimuth plane of the monitoring antenna. In the case of 50° latitude, for example, this means that the longitudinal station-keeping tolerance of a GSO space station is predominantly measured as angular difference in the azimuth plane of the antenna. It reaches the value ±0.13° for a longitudinal difference of 0° between monitoring station and sub-satellite point and drops to ±0.085° for a longitudinal difference of 60°. The corresponding measurement error in this example is ±0.01°, i.e. smaller by a factor of 10 compared to the allowable tolerance.

Figure 6-12 contains values for the half-power beamwidth and the pointing accuracy of an antenna as a function of frequency and reflector diameter. It is clear that full implementation of position monitoring as a monitoring task is subject to restrictions, especially in the case of lower frequency bands. Less stringent requirements allowing the use of smaller antenna systems are permissible in such cases where only greater divergences or deviations in position-keeping, for example in investigations of harmful interference, are to be identified.

6.1.3.6 System polarization

For polarization measurements (§ 6.1.2.5) the characteristics of the antenna system should be carefully considered. As circular and linear polarizations are used in the frequency bands above 1 GHz and use of dual polarizations in the frequency bands of the fixed-satellite service is a standard technique, it is necessary that the polarization of the receiving system can be adapted to that of the received signal and that a sufficient polarization discrimination is achieved.

Apart from enabling the polarization characteristics of the received signal to be obtained, such a system will also provide for maximum antenna gain and maximum reduction in the crosstalk signals between the two orthogonal polarization planes, which is a requirement for most of the measurements indicated in § 6.1.2.

6.1.3.7 Receivers

For economic reasons and because general coverage is required at monitoring stations, the extremely low noise figures of the fixed-frequency receivers used for space research and operational purposes are not reached by tuneable monitoring receivers. Nevertheless, the noise figure of the receiving system for a monitoring station for space services affects the total system noise figure. Its reduction to the lowest possible value is an important goal during the design phase of a monitoring station for space services. This is true even though it is possible in nearly all cases to improve the signal-to-noise ratio by narrow band filtering of a part of the emission spectrum.

For frequencies below about 3 GHz, standard monitoring receivers may be used. Above about 3 GHz a microwave receiver system of modular design should be used to meet the various requirements. The conventional concept, where the receiver comes as a self-contained unit, cannot be used, as, due to the high cable losses in the microwave range, the front end of the receiver must be situated close to the antenna, whereas the low-frequency modules and the control facilities can be located in the operating room. An example of receiving system specifications for C and Ku bands is given in Table 6-3.

TABLE 6-3

Example of receiving system characteristics

Tuner and synthesizer	
Frequency range	1-18 GHz with several overlapping tuners
Receiving frequency bandwidth	Centre frequency ±50 MHz
Frequency error	$< \pm 2.5 \times 10^{-8}$
IM-free dynamic range	> 66 dB (1 MHz bandwidth)
Oscillator phase noise	< −90 dBc (Hz) (10 kHz from carrier)
Broadband receiver	
Minimum tuning step	1 kHz
IF filter bandwidth	0.05/0.3/1.25/2.5/5/10/20/40 MHz

In the case of automatic methods for Doppler shift measurements, where a frequency counter is required, the receiver has to deliver a noise-free output signal, which accurately represents the satellite carrier frequency. For this purpose, the receiver must provide phase-locked synchronization to the satellite carrier frequency.

The bandwidth of the loop should be able to be switched between a few hertz and a few hundred hertz. The output frequency of such a phase-locked circuit may also be used as a pilot frequency for the adjustment of the frequency of a second receiver during bandwidth measurements, as outlined in § 6.1.2.3.

For more general purposes, if a satellite signal without a carrier has to be received, and if the pfd of this signal is sufficient, an automatic frequency tuning device may be used to avoid distortion of bandwidth and pfd measurements due to Doppler shift in the received signal frequency.

The following receiver outputs should be provided to facilitate the taking of measurements: wideband and narrow-band intermediate frequency outputs, video frequency, audio frequency and baseband (AM/FM) outputs. The intermediate frequency should be the same for all the receivers of a measuring installation so that the same auxiliary equipment may be used with all the receivers.

6.1.3.8 Peripheral equipment

6.1.3.8.1 General equipment

Table 6-4 contains a list of some peripheral equipment, which is necessary for the above-mentioned measurements, and other useful equipment, which can be added to the receiving system.

6.1.3.8.2 Analyser

The spectrum analyser has proven to be one of the most powerful instruments not only for general monitoring, but also for space monitoring purposes. To enable it to be used for monitoring tasks, the spectrum analyser should be able to work interactively with other equipment under computer control.

To perform real time spectrum display and power measurements, a digital FFT or vector analyser can be used. The bandwidths and the appropriate filter curves for the different modulations (FM, QPSK, etc.) can be chosen by programming digital filters. FFT analyses show a realtime spectrum and do not need a significant period of time to sweep over the signal bandwidth like conventional spectrum analysers.

TABLE 6-4

Peripheral equipment

Necessary peripheral equipment		**Additional peripheral equipment**	
Type of equipment	**Function**	**Type of equipment**	**Function**
Frequency/time standard	Central reference	TV demodulator	Demodulation of FM- and digitally-modulated TV carriers
Frequency counter	Doppler shift frequency measurements	TV decoder	Decoding of TV baseband signals (NTSC, PAL, SECAM, HDTV)
Time divider	Timing pulse for frequency counter		
Signal analyser	Spectrum analysis, bandwidth measurements	Sound carrier demodulator	Demodulation of TV sound subcarriers, tunable
Power meter	PFD measurements		
Signal generator	Reference PFD measurements	Modulation analyser	Identification of types of modulations, modulation measurements
Recorder	General purpose		
Digital oscilloscope	General purpose		

6.1.3.9 Broadband RF or IF monitoring channel

It is recommended for the technical design of the receiving system of a monitoring station for space services to allow for the broadband monitoring of the radio frequency spectrum. Simultaneous analysis of a minimum bandwidth of 500 MHz should be provided for.

6.1.3.10 Radio-frequency spectrum recording equipment

The technical characteristics of the recording equipment for space monitoring (see § 6.1.2.9 for reference) correspond to those required for terrestrial monitoring purposes. Since non-directional antennas of preferably linear polarization have to be used, the loss in antenna gain has to be compensated for by a selecting a small bandwidth for the recording equipment. As a general rule, and particularly for graphical recording units, the total analysed spectrum bandwidth should not exceed 2 MHz.

6.1.3.11 Computer requirements

Computer requirements should be seen as an integral part of a monitoring station for space services. They can be used, for example, for:

– calculation of orbital elements;

– calculation of antenna pointing angles from orbital elements;

– antenna steering;

– storage of measurement results;

– evaluation of measurement results.

6.1.4 Documentation and database support to space monitoring

6.1.4.1 General considerations of documentation and database

Successful operation of a monitoring station for space services depends on the continual update of documentation. The preferable source of information would be the data officially published by the ITU.

Characteristics of space stations submitted by Administrations for updating the MIFR and the Space Plans can be found in the BR International Frequency Information Circular (BR IFIC) which are published once every two weeks by the Radiocommunication Bureau in accordance with provision Nos. **20.2** to **20.6** and No. **20.15** of the Radio Regulations and are distributed via on-line application, web-based distribution of ISO file and DVD-ROM. BR IFIC also contains the Space Networks Systems Database of the ITU Radiocommunication Bureau. The database contains the data items of Appendix **4** of the Radio Regulations related to geostationary and non-geostationary satellite systems, earth stations and Radio astronomy stations. It can also be accessed via the on-line tool ITU Space Explorer.

Other additional information can be also consulted on the ITU website (Space Networks Regulatory Hub), as the list of satellite systems bought into use or suspended from the use, as well as the list of non-GSO networks subject to the milestone-based approach in accordance with Resolution **35 (WRC-23)**.

In addition to the information published by ITU, other sources of information can be used to perform, a survey of all satellites in orbit, together with some of their most important orbital elements (time of revolution, inclination, apogee, perigee). The data of earth stations licensed by the administration are valuable in earth station geolocation, especially in identifying the unauthorized users of the spectrum.

To facilitate monitoring operation, it is necessary to establish a database in order to record two kinds of information. One is general information of all satellites of interest, and the other is the characteristics of the satellites that will be obtained by monitoring.

6.1.4.2 General information database of existing satellites

The database of general information of an existing satellite mainly describes the characteristics and the licensed space service of a satellite within the monitoring capacity of the station. The most important information includes:

– satellite orbital information, including nominal longitude of a GSO satellite, longitude tolerance, orbital elements information of a non-GSO satellite, etc.;

– transponder information, including number of transponders, bandwidth of transponders, frequency range, beacon frequency, maximum antenna gain;

– satellite beam information, including beam coverage, service area, maximum pfd.

Additionally, the following satellite information is useful in the geolocation of earth stations:

– geographic information, including longitude, latitude and altitude, etc.;

– satellite ephemeris information, which could be better presented in file format, including TLE, ECI, etc.;

– antenna information, including antenna size, gain, antenna pattern, etc.;

– other information, including frequency assignment, bandwidth, polarization, transmitting power, service type, modulation type, work time, etc.

Sources for the above information can be satellite operator(s), the administration(s), and public media.

6.1.4.3 Monitoring information database

The monitoring information database is used to record the measurement result of space monitoring station. The measurement result should include some key parameters, such as frequency, polarization, bandwidth, pfd, carrier C/N_0, modulation type, multiple access type etc. A long-term occupancy analysis of spectrum can facilitate the spectrum planning. Stored IQ data is helpful for conducting in-depth signal analysis (see Recommendation ITU-R SM.2117).

For the monitoring station with satellite geolocation capability, the measurement result should also include the longitude and latitude of the centre point of the area where the interfering transmitter is most likely located, and geolocation accuracy which could be represented by ellipse with major axis, minor axis and angle of the area relative to North. If the monitoring station is equipped with satellite ephemeris determination system, it is beneficial to store the latest and accurate ephemeris data of the satellites frequently used for geolocation.

To facilitate the data exchange between monitoring stations, the parameters of monitoring itself, such as position of antenna, antenna parameters, measurement time and weather etc., should be recorded in the database. The data and form for reporting the harmful interference cases to space radiocommunication services , the illustrations of different interference scenarios and example reports of the harmful interference are specified in Recommendation ITU-R SM.2149.

6.1.4.4 Using documentation and database to facilitate monitoring

In monitoring, documentation and database support the following purposes:

Identifying space stations

Space stations can be identified through a comparison between the general information database and monitoring data. The detailed introduction to the process of identifying space stations will be given in the following section.

Identifying illegal emissions

Monitoring engineers can identify illegal emissions through comparison of corresponding entry in the general information database which has been approved by the administration. This can be achieved automatically by monitoring systems.

This is only applicable when the approved data of the carriers is available to the administration.

Facilitating the geolocation of emissions

Database systems can remarkably improve the efficiency of geolocation missions. Analysis can be performed based on the information in the database, including:

– adjacent satellite analysis;

– reference signal selection;

– potential interferer analysis.

In addition, geographic information systems (GIS) play an important role in space monitoring, a joint system of station database and GIS database can give the monitoring engineer an overview of the use of the spectrum. Such a joint system can be used in analysis of potential interferers to space stations.

6.1.5 Identification of space stations and geolocation of earth stations

The identification of a space station is generally based on the comparison of the measured emission and orbital characteristics with those found in the reference database and documentation. Reference characteristics consist of a list of the emission and orbital characteristics of all space stations, which have been published or made available to the monitoring service. The unknown station is identified by the iterative elimination of those stations, which do not correspond to the measured characteristics. Reference characteristics are given in Table 6-5.

TABLE 6-5

Reference characteristics

Emission characteristics	Orbital characteristics
Frequency	Ephemeris data, or, if not available:
Bandwidth	– period of revolution
Type of modulation	– angle of inclination of orbit
Polarization	– perigee and apogee distances
e.i.r.p.	– equator crossing time and longitude of crossing

With the wide use of GSO satellites, it is necessary for administrations to be able to identify earth stations transmitting toward GSO satellites. This is done to acquire complete information of the use of earth stations and eliminating harmful or illegal emissions. When using the geolocation method described in §§ 6.1.2.7 and 6.1.2.9, positional inaccuracies typically can be a few kilometres to tens of kilometres. This accuracy may be sufficient for identifying emissions from legitimate users, As for the illegal emissions, other terrestrial monitoring means may be required to finally pinpoint and eliminate the interference.

6.1.5.1 Monitoring results to be used for identification

6.1.5.1.1 Evaluation of frequency band recordings

With reference to § 6.1.2.10 and to the example given in § 6.1.7.1, approximate values for the following space station characteristics can be obtained from frequency band recordings:

– frequency;

– expected time of reception for non-GSO satellites;

– period of revolution.

6.1.5.1.2 Calculation of period of revolution

For the calculation of the period of revolution with an accuracy level of several seconds, it is possible to obtain an initial approximate value by measuring the times of TCA of two successive paths. A refined result is then based on additional TCA measurements over a period of one or two days.

6.1.5.1.3 Direction-finding

To complement the determination of the exact TCA of a satellite to a monitoring station, a curve can be plotted to show the change in direction of arrival of the signal with time, as determined by Direction-finding (DF) bearings or orientation of a highly directional receiving antenna. The maximum angular rate of change will occur when the satellite is nearest to the monitoring station during a particular pass, and the information obtained by this method should agree with the information obtained from the Doppler shift curve.

DF measurements are well suited for the determination of the TCA in cases where a carrier frequency does not exist within the spectrum. However, DF measurements require a sufficient pfd at the receiving point.

6.1.5.1.4 Calculation of ephemeris data from antenna angle measurements

If a monitoring station is equipped with an auto tracking antenna system, angle measurements in the azimuth and elevation planes may be used to calculate the ephemeris data of the unknown satellite [Montenbruck, 1989] and [Montenbruck and Pfleger, 1991]. Software to carry out the calculations is commercially available.

The accuracy in determining the ephemeris data depends on:

– overall angle measurement accuracy (§ 6.1.3.5);

– orbit segment used for angle measurements;

– type of orbit of the satellite.

A significant operational problem is the need to point the antenna quickly at a non-GSO satellite soon after its entry into the visibility range of the monitoring station. While the need to obtain accurate angle measurement requires highly directional antennas, their use increases the difficulty of searching for and finding a LEO satellite since the portion of the orbit that can be used for measurements is less than the total visible orbit. One example illustrating the calculation of orbital elements on the basis of angle measurements is found in § 6.1.7.2.

6.1.5.1.5 Emission characteristics

Measurements of the emission characteristics as outlined in the sections above may be sufficient for the identification of a space station. This is particularly the case for those space stations which are operated in accordance with the RR and whose emission characteristics are notified or published.

6.1.5.2 Identification procedure

If the measured emission characteristics do not result in the identification of a space station, the measured ephemeris data, or parts thereof, may be of help.

When comparing the measured ephemeris data with the published reference data, the orbiting objects with the most similar data are selected first. Subsequent step-by-step comparison of the data should result in a significant reduction in the number of objects to be considered. Finally, by calculating the visibility times and the TCA for the remaining objects and by comparing them with the monitored results, it should be possible to achieve correct identification.

6.1.5.3 Other possibilities for identifying space stations

The procedures that have been discussed so far for the identification of space stations have been based on comparing the measured and observed signal characteristics with published information, and by comparing the measured ephemeris data or parts thereof (time of revolution, inclination angle, TCA) with published ephemeris data. This procedure is, however, time consuming and requires access to the ephemeris data of the objects in orbit.

In some cases, particularly when non-compliance with the RR or where cases of harmful interference are observed, an additional procedure may be useful. In these cases, the monitoring station for space services could log all possible information concerning frequency and bandwidth measurements and other emission characteristics, together with ephemeris data, or parts thereof, and request identification based on this data from identification and tracking centres or from satellite network operators.

6.1.5.4 Operational considerations regarding the geolocation of uplinking earth stations toward GSO satellites

At present, there are commercial geolocation systems from different manufacturers available, these systems generally use the principles described in § 6.1.2.7 and § 6.1.2.9 to geolocate uplinking earth stations toward GSO satellites, and are adopted by some satellite operators and administrations. Certain operational considerations of these systems are presented here in this section.

At the outset, the operator of the geolocation system should first determine the nature of the unknown signal. This can be done in two ways: by means of other monitoring facilities, or getting information from the satellite operator. Then one or two adjacent satellites are required for the test. The operator may have multiple choices when evaluating the candidate adjacent satellites. He should also input other required information into the geolocation system. Usually reference signals are required to either cancel the drifts in the oscillators on board the main and adjacent satellites, or be used in the geolocation algorithm to correct the position fix inaccuracy as a result of ephemeris errors.

6.1.5.4.1 Acquisition of necessary information

The operator should know some useful information regarding the signal under test. For example, the satellite carrying the unknown signal, the frequency plans of its transponders, the centre frequency, bandwidth, duty cycles (for intermittent signals) and the frequency mobility characteristics of the unknown signal. Based on this information the operator will select the appropriate observing parameters to optimize the likelihood of successful geolocation.

The above information can be acquired by other monitoring means, or, if the unknown signal being harmful interference, provided by the victim.

It is also helpful to record the interfered transponder of the satellite with a spectrum recorder as soon as possible after the interference is reported to the monitoring station. That allows seeing the activities of the interferer and the transponder occupancy.

6.1.5.4.2 Adjacent satellite selection

There may be more than one suitable satellite that can be used as adjacent satellites. The primary consideration in doing this is to assure that the selected adjacent satellites have the proper uplink and downlink connectivity.

From the known downlink frequency and polarization for the unknown signal, the operator may infer the corresponding uplink frequency and polarization for the unknown signal. In the case where either hemispherical or spot uplink beams are employed, the uplink beam pattern may limit the geographical region from which the unknown signal is likely to originate. The operator should keep in mind, however, that large uplink antennas residing outside of the main beam pattern of the satellite uplink beam interference may cause interference as well.

From a consideration of the unknown signals uplink frequency and polarization and the beam coverage of the primary satellite's uplink antenna, the candidate adjacent satellite(s) can be found. These criteria for selecting the adjacent satellite are:

– same uplink frequency coverage as the primary satellite;

– same uplink polarization as the primary satellite;

– similar uplink beam coverage as the primary;

– angular separation from the primary satellite along the geostationary arc;

– transponder does not use on board processing.

The primary selection criteria listed above are ordered roughly according to their relative importance. The first two criteria, uplink frequency, uplink polarization and downlink beam coverage, are absolute prerequisites to successful measurements.

Once the operator has identified one or more candidate adjacent satellites based on the above-mentioned criteria, the secondary criteria can be used to help guide the final selection.

These secondary criteria include:

– availability of adequate reference signals for the primary/adjacent satellite pair;

– quality of the ephemeris data available for the adjacent satellite;

– presence/absence of signals in the transponder of the adjacent satellite corresponding to the frequency of the interferer signal.

In making the final choice of adjacent satellite, the operator should keep in mind that the optimum geometric solution will be obtained for satellites with good quality current ephemeris data and an adequate selection of reference signals for the satellite pair to be used.

Reference signals may appear on either the primary or adjacent satellite. If adequate reference signals are available on the primary satellite, this criterion need not drive the selection of the adjacent satellite. Dedicated reference transmitters, fixed or transportable, can also be used to improve the geolocation result.

An additional factor that may influence the selection of adjacent satellite is orientation of the FDOA lines for the chosen satellite pair at the time of measurement. Unlike the TDOA lines, the orientation of the FDOA lines for a given satellite pair can vary significantly over the course of an orbital period (1 day).

The best choice is to find an adjacent satellite without signals around the interferer signal and the reference signals. To observe the actual transponder activities, it is recommended to record the transponder of the adjacent satellite with a frequency spectrum recorder facility.

If the measurements are taken when the FDOA lines are nearly parallel to the TDOA lines, the result area will be highly elongated along the lines of constant TDOA. In such circumstances the operator should consider either choosing a different adjacent satellite or scheduling additional measurements at a time when the FDOA line orientation is more favourable.

6.1.5.4.3 Reference signals

An ideal reference signal is a full time broad-banded signal uplinked from a precisely known geographic location that produces strong correlation on the two satellites being used. This precise location can be obtained from the database of earth stations, but preferably double-checked with a portable GPS receiver. In such case that reference signals are abundant, the operator should try to use reference signals:

– uplinked from a relatively small antenna;

– which are well distributed geographically;

– with suitable modulation;

– whose frequency is unused transponder sections on the adjacent satellites.

6.1.5.4.4 Ephemeris data

The quality of the ephemeris data for both the primary and adjacent satellite will directly impact the quality of the result. In most cases, the error in the ephemeris can be eliminated to a large extend by using two or more reference signals (see § 6.1.2.7.2 for detailed information). If the ephemeris data is particularly bad, as may be the case immediately following manoeuvres or when the epoch of the ephemeris data is several days prior to the date of the measurements, position uncertainties as large as several hundred kilometres may result. In this case the operator should strive to either obtain better ephemeris data or use an alternate adjacent satellite.

The operator of the geolocation system can acquire ephemeris data in the following way:

– request data from the satellite operator(s);

– download the published data from websites;

– determine the satellite ephemeris by specialized measurement system.

Check the ephemeris data with a geolocation measurement of a known (e.g. reference) station. If the quality of the result is not sufficient, an ephemeris error compensation can be applied. This is a capability to compensate satellite ephemeris errors.

With three or more reference stations, a geolocation measurements are carried out. The ephemeris error compensation corrects the ephemeris data with an inverse calculation of the geolocation measurements.

The satellite ephemeris data with higher precision could be measured in an active way or a passive way by specialized measurement system, as detailed in § 4.7 of Report ITU-R SM.2424.

6.1.5.4.5 Establishment of dedicated supplementary reference transmitters

The operator of the geolocation system may find the number and the geographic distribution of reference signals not sufficient to yield accurate result in some circumstances. On some satellites, most of its users are located in one or two major cities, which significantly limit the number of reference signals available for geolocation. Therefore, it is necessary for administrations to establish a number of dedicated supplementary reference transmitters to provide the operator of a geolocation system more choices in terms of reference signals. These transmitters should:

– meet the technical requirements of satellite operators;

– be able to point to any visible GSO satellites along the geostationary arc;

– be well distributed geographically;

– have relatively small antenna sizes;

– use suitable modulation type(s).

It is advisable for administrations to cooperate in establishing dedicated supplementary reference transmitters at different locations, and use them as a reference when necessary.

Before using the dedicated supplementary reference transmitters to transmit toward a certain satellite, prior consent of the satellite operator is required. And certain technical tests may also be required before transmitting.

6.1.5.4.6 Transportable reference transmitter

Generally, it is very hard to search for a transmitter uplinking to a GSO satellite, especially in an urban area. Two major factors lead to these difficulties, one being the losses of radio-waves by buildings, the other the normally high directivities of antennas which produces very weak side lobes in the terrestrial direction. Therefore, it would be useful to use the TDOA and FDOA measurement with the help of transportable transmitters to help pinpoint the transmitter, typically a harmful interference.

As mentioned in the previous section, before transmitting toward a certain satellite, prior consent of the satellite operator is required. And certain technical test may also be required before transmitting.

Theoretically, given a satellite pair, two earth stations transmitting at different frequencies produces the same TDOA value and two FDOA values with a very small difference. The closer the reference transmitter is to the unknown interferer, the better accuracy the geolocation algorithm will yield.

Before using the transportable reference transmitter, the operator should make full advantage of all fixed reference transmitters to minimize the inaccuracy of the result and the size of the resulting area. After that prior consent should be obtained from the satellite operator to transmit with regard to the technical parameters of the transmission. Then the following two steps should be taken:

Step 1: Move the transportable reference to the centre of the result area and transmit the reference signal as agreed by the satellite operator. Then the operator of the geolocation system should be notified to perform the geolocation measurement. The operator should also be notified the accurate position of the vehicle.

Step 2: The geolocation measurement yields a new result using the transportable reference transmitter.

The result will be refined after the second step, and these steps can be repeated to get even better result.

The operator of the transportable transmitter should keep close contact with the operator of the geolocation system. In practice, the selection of route and the transmission will be affected by many other factors such as traffic regulations and the operator should take note of these factors.

6.1.6 Technical solutions by examples

6.1.6.1 Example of a space radio monitoring station

This section describes the principle composition of a space radio monitoring station. In principle it is made up of four technical main parts:

Part 1: Antenna system (see § 6.1.6.1.1)

One or more different antennas for all the telecommunication and space radio frequency bands of interest. (directional and omnidirectional antennas).

Part 2: Receiving facilities (see § 6.1.6.1.2)

Feed systems, polarization unit, down-converters, calibration system, reference frequency source.

Part 3: Monitoring equipment (see § 6.1.6.1.3)

Both automatic measurement systems and manual measurement and analytic facilities like signal analysers, receivers, spectrum recording systems and modulation analysers are part of the monitoring equipment.

Part 4: Control facilities (see § 6.1.6.1.4)

The control facilities comprising the hardware and software for the control of the antenna positioning, the settings of the receiving system and the settings of the monitoring equipment facilitate automatic measurement procedures.

General

Location of the monitoring station:

The monitoring station should be as far away as possible from urban and industrial areas with man-made noise, cell phones and RLANs. Fixed links should not cross the location of the site. A protected area around the monitoring station should be declared and kept free from terrestrial transmitters and fixed links.

The landscape around the monitoring station should be flat without obstructing the line of sight due to hills and buildings.

Site configuration:

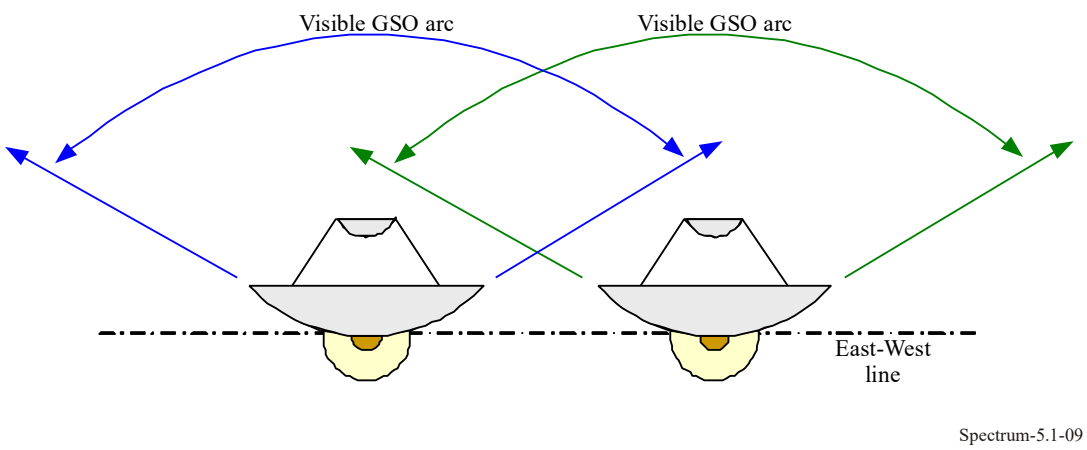
The location of the antennas and the buildings depends mainly on the target of monitoring (GSO or non-GSO satellite) and which part of the geostationary orbit that will be of interest. Future expansions should be taken into account.

For even and open conditions, the antennas can be arranged on a line, e.g. East-West-Line.

The distance between antennas directed toward GSO satellites only, the visible angle of the geostationary arc has to be free of obstacles (see Fig. 6-13).

FIGURE 6-13

Separation of GSO satellite monitoring antennas



For the unhindered receiving of non-GSO satellites the area around the antenna must be free of obstacles (antennas, buildings) in all directions at least up to the lowest required elevation (see Fig. 6-14).

FIGURE 6-14

Example of elevation of non-GSO satellite monitoring antennas

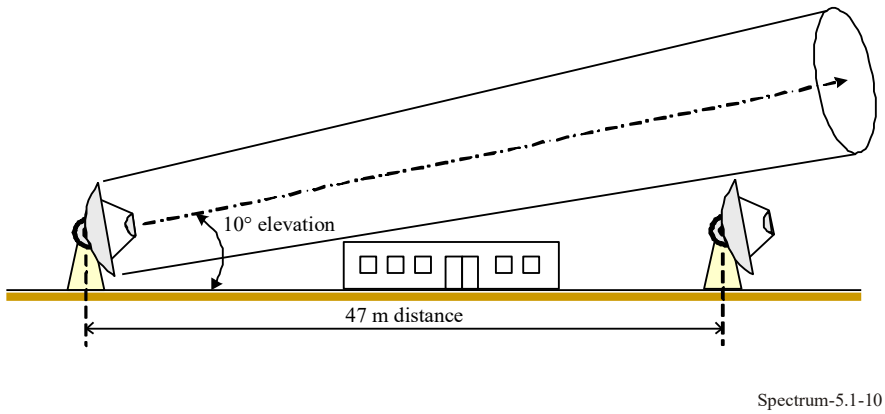


Table 6-6 shows the ideal distance between two antennas (9 m diameter each) for clear line of sight to the satellites. The elevation angle is the lowest angle for an unblocked view to the satellite.

In order to optimize the number of antennas needed, combination of receiving bands shall be preferred, without significant deterioration of the antenna performances. A geolocation measurement system requires two antennas each covering the desired frequency band.

For example, a combination of three antennas (1 C/Ku, 1 L/S and 1 Ka) offer the possibility to receive applications like broadcast links, networks and satellite control and test signals optionally. It is also possible to combine four or five frequency bands in only one antenna. This can be achieved by using a Cassegrain antenna with a beam waveguide system and two cabins or by using a revolving feed system.

The disadvantage of such a multi-band antenna is that only one frequency band can be used at the same time.

TABLE 6-6

Distance between two antennas (of the same size) for clear line of sight to the satellites

Elevation (degrees)	Distance (m)
5	99
10	47
15	30
20	22
25	18
30	16

6.1.6.1.1 Antenna system

Antenna concepts in principle

Satellite monitoring operations utilize various antenna configurations, each designed for specific operational requirements:

– Limited motion antenna

– Turning head antenna with continuous azimuth travel range of exceeding 180°

– Full motion antenna with elevation axis above azimuth axis

– Full motion antenna with elevation axis above azimuth axis above tilt axis

– Full motion antenna with slant axis above azimuth above tilt axis

– Full motion antenna with X-Y mounting

– Hexapod

– Phased array antenna.

The selection of appropriate antenna systems for monitoring GSO or non-GSO satellites requires consideration of specific antenna types optimized for their respective orbital characteristics. The following describes commonly used antennas.

Antennas for GSO satellite monitoring

GSO satellites maintain fixed positions relative to Earth's surface. Monitoring stations typically employ parabolic reflector antennas with rotational capabilities to maintain pointing toward target satellites.

Applicable tracking systems include:

– Computer-controlled tracking with two-line elements (TLE) sets

– Step-track systems

– Monopulse tracking.

Antennas for non-GSO satellite monitoring

Non-GSO satellites traverse continuously along their orbits, requiring monitoring systems capable of tracking rapidly moving satellite targets. Implementation options include:

– full-motion mechanical antennas with enhanced angular velocity capabilities and precision tracking systems;

– phased array antennas with electronic beam steering functionality.

For mechanical antenna implementations, performance requirements vary according to pedestal configuration (elevation-over-azimuth or X-Y mounting), with differentiated specifications for angular velocity and acceleration parameters. Phased array antenna implementations require specialized beam-forming algorithms and predefined scanning trajectories integrated within the tracking subsystem.

Applicable tracking systems include:

– Computer-controlled tracking with TLE sets.

– Monopulse tracking.

Azimuth-Elevation antenna

The azimuth-elevation antenna features an elevation axis above the azimuth axis, as illustrated in Fig. 6-16. This configuration provides operational capability for monitoring satellites with orbital trajectories up to 85° elevation angle. A zenith keyhole limitation exists in this configuration. The design accommodates various receiving equipment mounting options, including a cabin directly attached to the antenna reflector structure.

Effective tracking of satellite orbits up to 85° elevation with this antenna configuration requires azimuth rotational velocities of approximately 15°/s, dependent on satellite altitude parameters. For low-orbiting satellites traversing high elevation angles, insufficient azimuth velocity leads to significant risk of tracking loss.

Figure 6-17 illustrates the functional relationship between satellite orbital parameters, required azimuth rotational velocity, and the maximum attainable elevation angle.

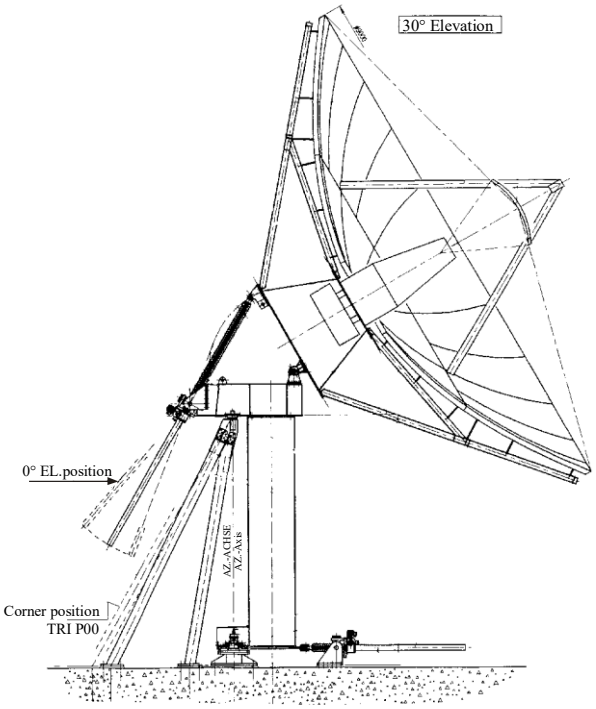
Three-axis Antenna

The three-axis antenna extends the standard Azimuth-Elevation (Az/El) system with an additional tilt axis to address tracking requirements for satellites passing overhead, as illustrated in Fig. 6-18. This design enables antenna rotation throughout a wider angular range (including zenith positioning), eliminating the zenith keyhole limitation. The three-axis system provides enhanced tracking precision and motion smoothness, suitable for applications requiring high positional accuracy.

This implementation requires precise orbital parameter information (e.g. TLE sets) for advanced tilt angle computation. The enhanced tracking capability comes at the cost of increased mechanical complexity and higher implementation costs. The tilt axis configuration is unsuitable for satellites with unknown orbital parameters, which require alternative tracking methods such as monopulse tracking systems.

FIGURE 6-15

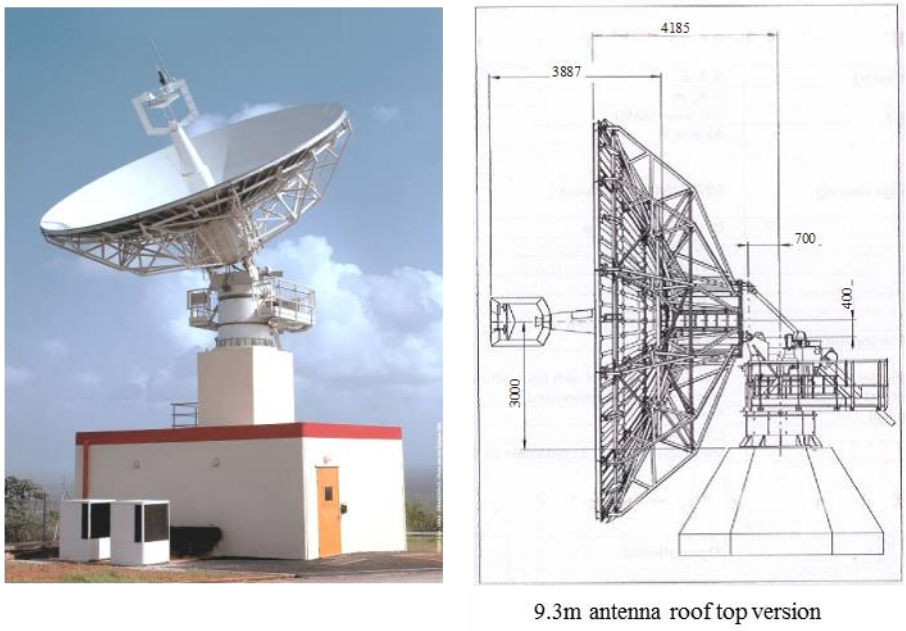
9 m limited motion antenna with Kingpost Pedestal and motorized jackscrews in azimuth and elevation



Spectrum-5.1-11

FIGURE 6-16

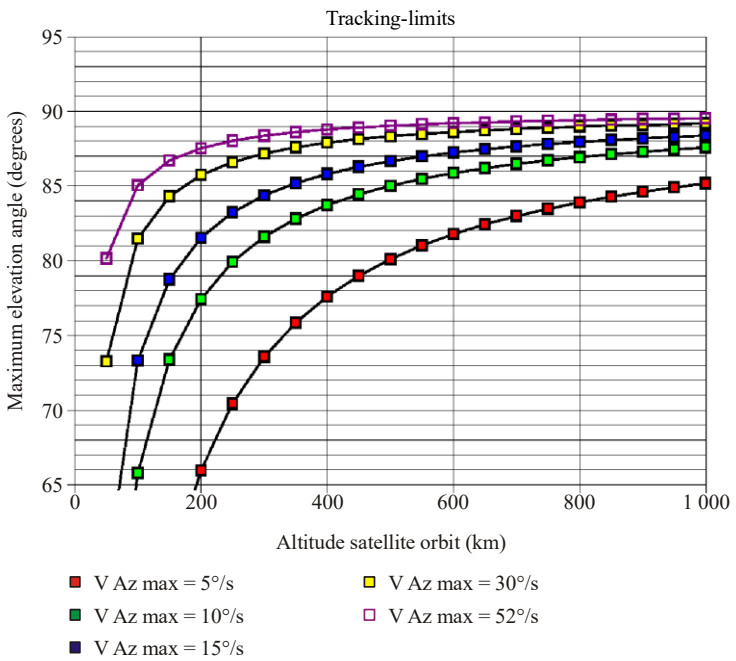
Example: 9.3 m turning head antenna



Spectrum-5.1-12

FIGURE 6-17

Relationship between satellite orbit, elevation angle and azimuth velocity for the antenna type elevation axis above azimuth axis



Spectrum-5.1-13

FIGURE 6-18

12 m Cassegrain beam waveguide antenna with an elevation above azimuth pedestal and two cabins for the receiving facilities at the rear side of the dish

Spectrum-5.1-14

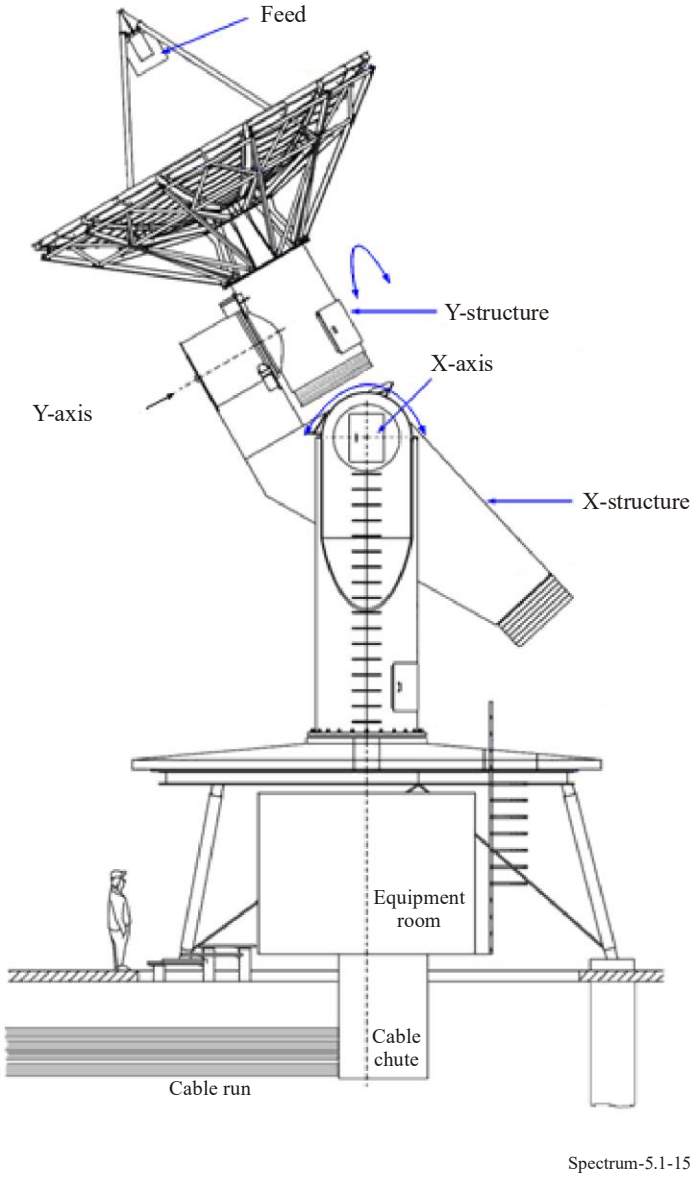
X-Y antenna

The X-Y antenna employs two mutually perpendicular rotational axes, designated as the X and Y axes, as illustrated in Fig. 6-19. This configuration tracks satellite trajectories through rotation about these two axes. Its advantages include a relatively simple mechanical structure, ease of manufacture and maintenance, and lower implementation cost.

A significant limitation of the X-Y antenna is the presence of a zenith keyhole; when satellites traverse the zenith position (overhead relative to the ground station), the antenna must execute rapid, large-angle rotational movements, potentially resulting in tracking interruption.

FIGURE 6-19

7 m X-Y prime focus antenna



Phased array antennas

Phased array antennas employ electronic control mechanisms to achieve beam steering capabilities without mechanical movement. This functionality is achieved by adjusting the phase of the signal at each radiating element within the array, enabling instantaneous beam direction changes essential for continuous tracking of rapidly moving non-GSO satellites, particularly those satellites in LEO. These systems offer simultaneous multi-satellite monitoring through multi-beam formation techniques, providing significant advantages for large-scale satellite constellation monitoring applications.

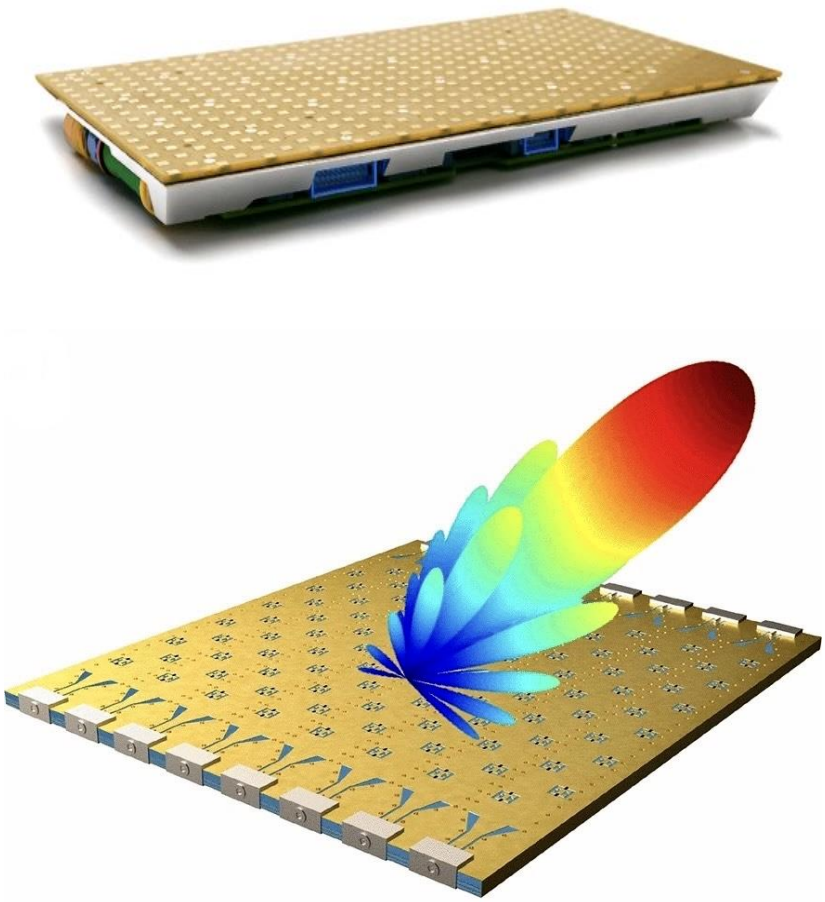
The electronic steering characteristics of phased array antennas facilitate integration into automated satellite monitoring systems. The absence of mechanical steering components confers several operational benefits including reduced system maintenance requirements and elimination of potential mechanical failure modes, thereby enhancing overall monitoring system availability.

A notable limitation of phased array systems is performance degradation at large scanning angles, characterized by beam broadening and gain reduction as the scanning angle increases. This phenomenon necessitates consideration in operational parameter measurements and coverage requirement assessments, requiring appropriate compensation techniques to maintain monitoring accuracy across the full scanning range.

Figure 6-20 illustrates an exemplary phased array antenna.

FIGURE 6-20

Example of the phased array antenna



Antennas specification

Table 6-7 provides technical specifications of practical satellite monitoring antennas. These parameters represent typical minimum specifications, as requirements vary depending on the monitoring station configuration. The actual parameters should be determined according to specific measurement requirements.

TABLE 6-7

Technical specifications of practical satellite monitoring antennas

Parameter		**Performance**		
		L/S/C-Band	**Ku-Band**	**Ka-Band**
Frequency range		L band: 1 452-1 492 and 1 530-1 800 MHz S band: 2 100-2 300 MHz 2 500-2 690 MHz C band: 3 400-4 200 and 4 500-4 800 MHz	10.70-12.75 GHz	17.30-21.20 GHz
Maximum signal level at the input of Low noise amplifier (LNA) (dBm)		≤ −30	≤ −30	≤ −30
pfd measurement performance (*C*/*N* at least 23 dB)		−155 dBW/m^2 in 4 kHz bandwidth	−165 dBW/m^2 in 4 kHz bandwidth	−160 dBW/m^2 in 4 kHz bandwidth
pfd measurement accuracy (dB)		±1	±1	±1
Figure of Merit (*G*/*T*) (dB/K)		L = 20 S = 23 C = 28	37	33
Reference frequency accuracy		Aging: one part in 10^{10} per day, Temperature: one part in 10^9 0° to 50° total change		
Polarization		X, Y, left-hand circular, right-hand circular		
Frequency resolution (kHz)		1		
Dynamic range (dB)		≥ 60		
Antenna	Dish diameter (m)	≥ 9	≥ 9	≥ 4.5
	Pointing accuracy (degrees)	0.15-0.04	0.02-0.017	0.025-0.02
	Beam width (degrees)	1.6-0.5	0.22-0.18	0.27-0.22
	Step-track speed for GSO satellites (degrees)	0.02-2/s, manual drive and auto step track (depending on the antennas location longitude and latitude)		
	Coverage for GSO satellites (degrees)	EL: 0 to 90, AZ: ± 60		
	Coverage for non-GSO satellites (degrees)	EL: 0 to 85, AZ: ± 270°(total azimuth coverage 360), store at 90		

NOTE 1 – The frequency ranges in this Table and other sections in § 6.1 (e.g. L, S, C bands) are not formally defined in the ITU-R, but are widely used in the satellite communication community.

NOTE 2 – For the measurement of out-of-band emissions, the mentioned commercial frequency bands must be enlarged. Strong terrestrial emissions have to be blocked with filters.

6.1.6.1.2 Receiving facilities

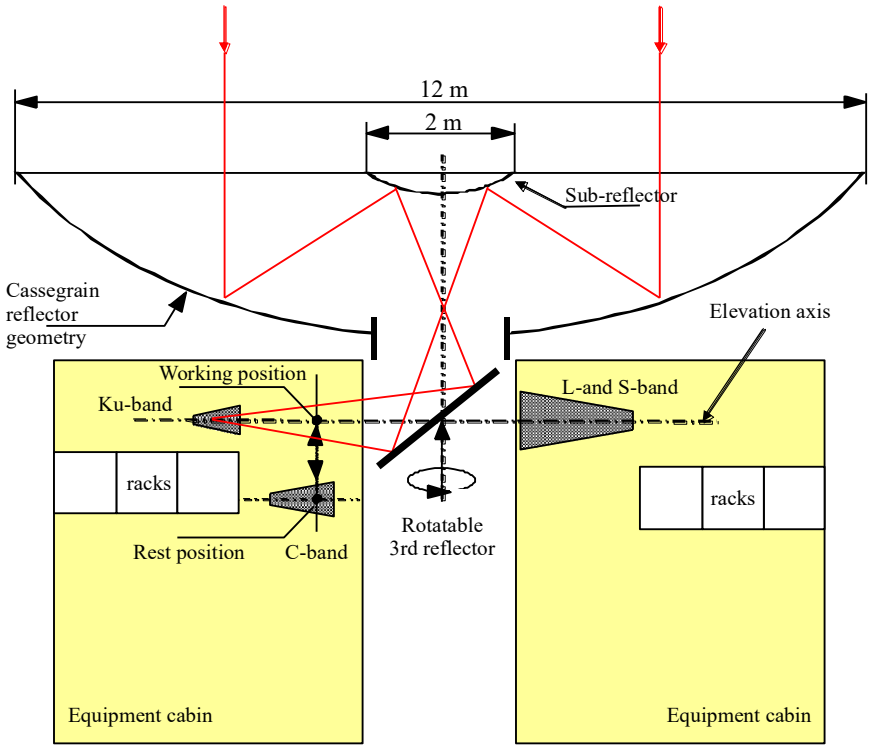
The advantage of a beam waveguide system is that the beam can be directed to different locations with low insertion loss.

The feeds can be accommodated in equipment cabins providing sufficient space for the installation and maintenance of equipment and air condition.

The feed systems for satellite monitoring antennas are relatively unique, since these antennas are used for receiving only, and generally cover a wide frequency range.

FIGURE 6-21

Example: Separated feeds with a moveable feed and a select reflector layout for 3 frequency bands into a 12 m beam waveguide antenna



Spectrum-5.1-16

FIGURE 6-22

Example: Fixed feeds with moveable select reflectors layout for 5 frequency bands into a 12 m antenna

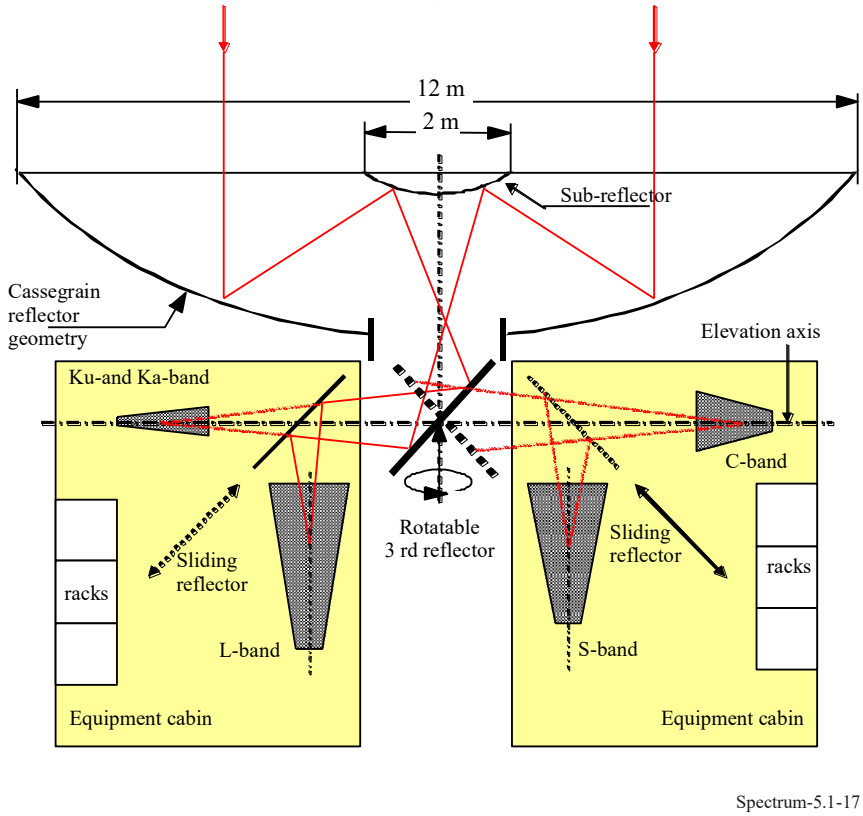
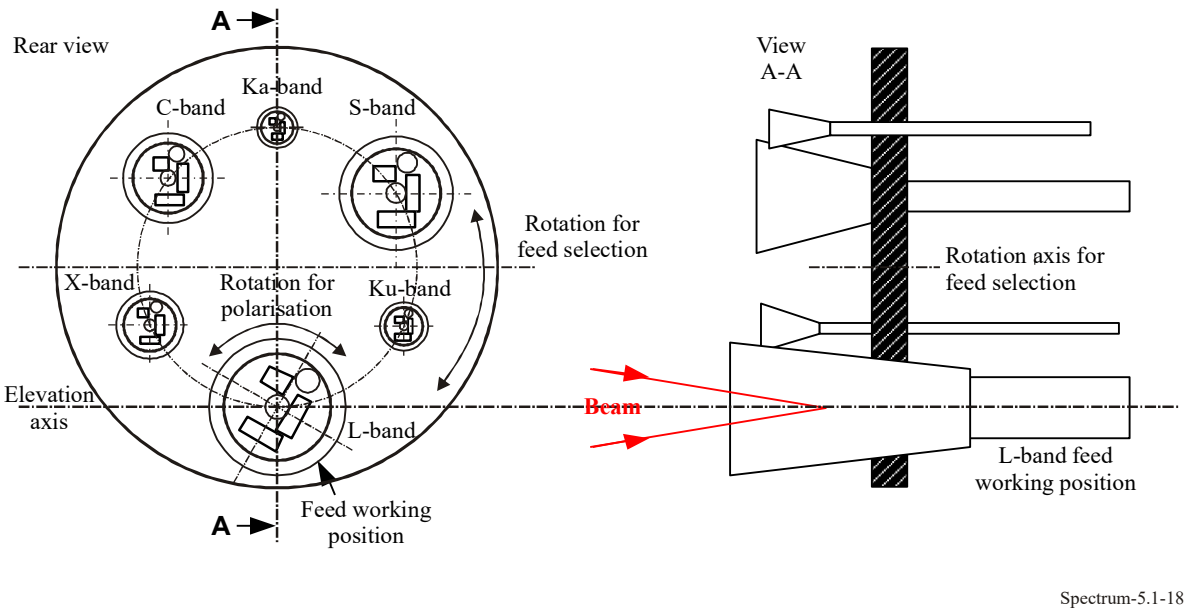


FIGURE 6-23

Example: Multi feed revolver system with 6 feeds for a beam waveguide antenna



Example: Multi feed revolver system with 8 feeds for a prime focus antenna

Frequency range: 1 GHz-26.5 GHz without frequency gaps.

Feed 1 up to 6 (frequency range 1 GHz-12.75 GHz) are crossed dipoles with cavity design.

Feed 7 and 8 (frequency range 12.5 GHz-26.5 GHz) are horn antennas.

Outdoor case dimension: around 700 × 700 × 500 mm [$W \times D \times H$]

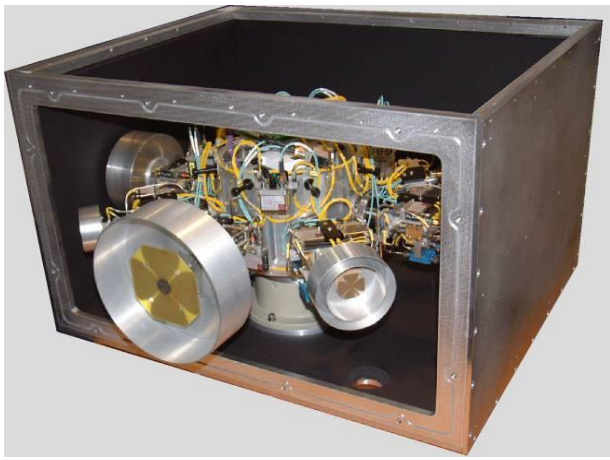
FIGURE 6-24

Multi feed mounted in prime focus

Spectrum-5.1-19

FIGURE 6-25

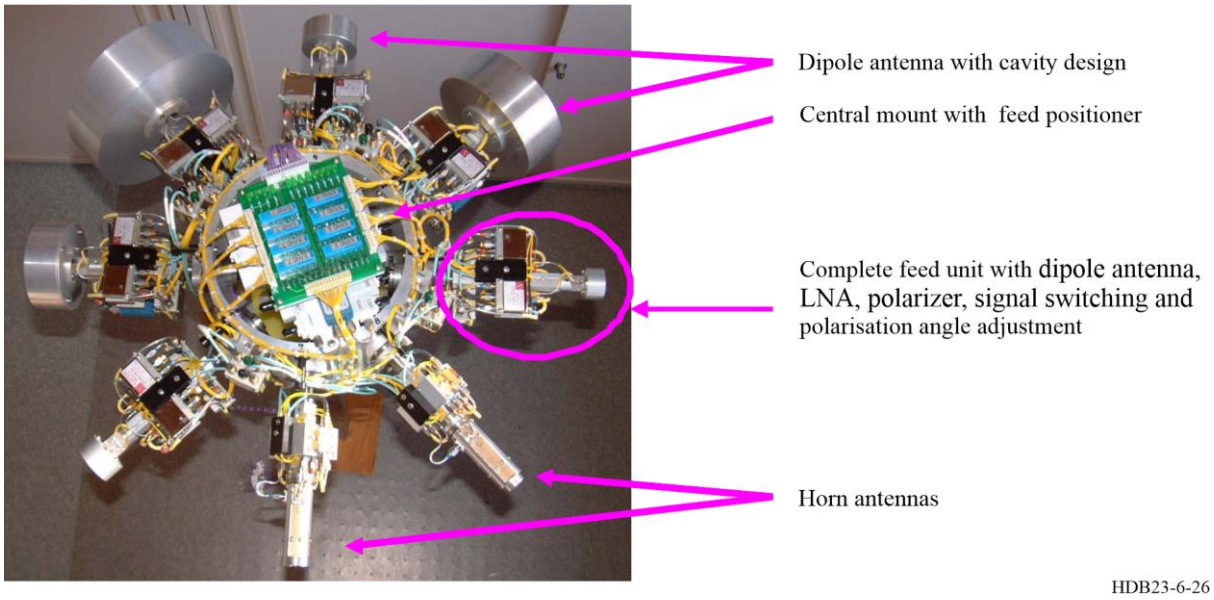
Multi feed in the open outdoor case



Spectrum-5.1-20

FIGURE 6-26

Feed without outdoor case mounted around the feed positioner



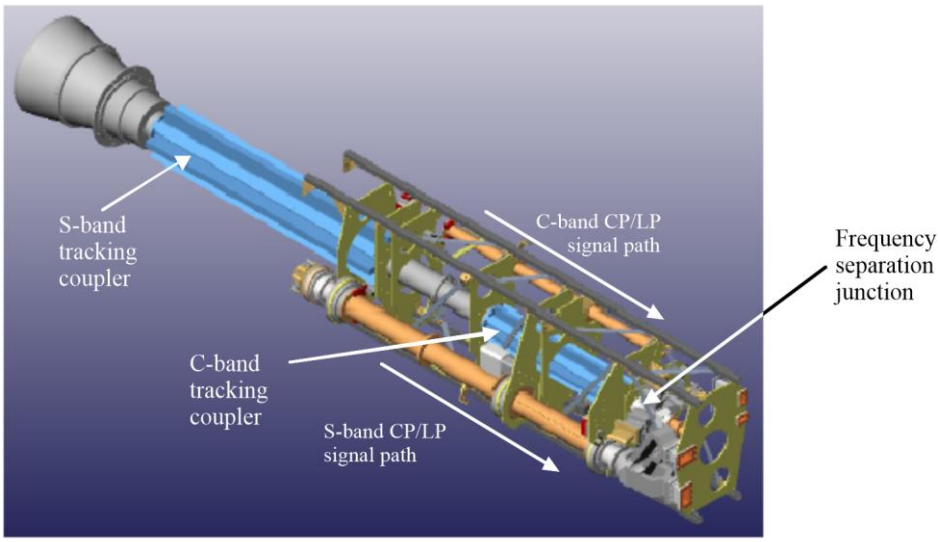
All feeds designed in coax technique for linear and circular polarization and polarization angle adjustment of ±95°.

FIGURE 6-27

Example: Combination of 3 frequency bands into a 12 m antenna

Feed system for Cassegrain antenna configurations 11 m and larger. CP/LP switching, independent LP polarisation adjustment and monopulse tracking in both bands.

S-band: 2.1-2.7 GHz
C-band: 3.4-4.8 GHz



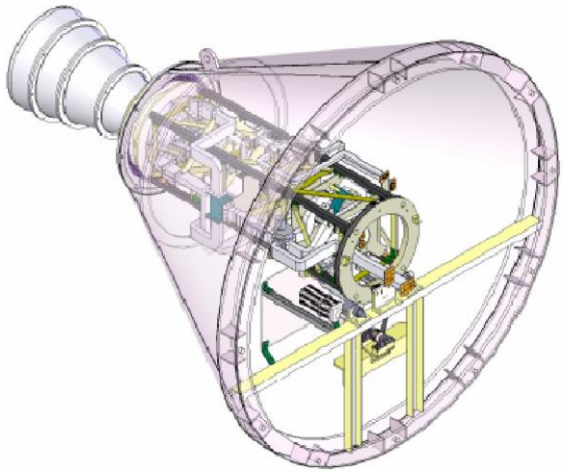
HDB23-6-27

FIGURE 6-28

Example of feed with two closely spaced frequency bands

Feed system for Cassegrain antenna configurations 9 m and larger.

C-band: 3.4-4.2 GHz, CP/LP
X-band: 7.25-8.4 GHz, CP
Ku-band: 10.9-12.75 GHz, CP/LP



Spectrum-5.1-23

Receiving equipment

The receiving equipment comprises the following items in Table 6-8:

TABLE 6-8

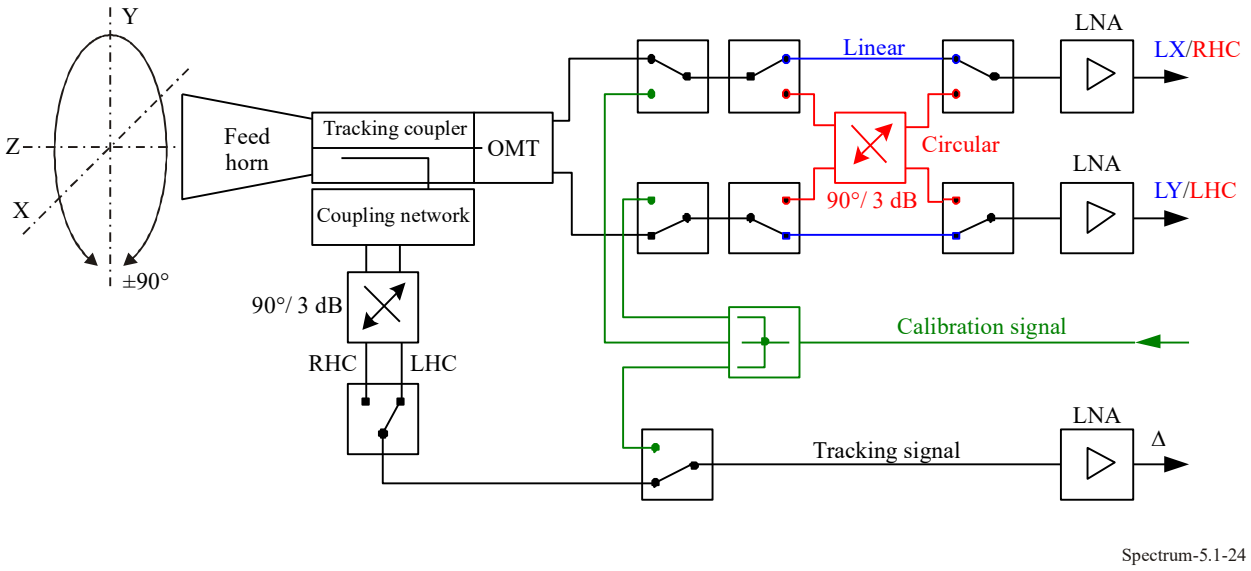
Receiving equipment of an antenna system

Feed	Horn-, dipole- or cross dipole-antenna and the coupling network
Tracking coupler	Coupling out the TE21 mode for the monopulse antenna tracking
Polarization adjustment	Rotator for the adjustment of the polarization angle
Orthomode transducer (OMT)	Separation of the polarization planes X and Y in two channels
Low noise amplifier (LNA)	First amplifier with a noise figure as low as possible
Polarizer	Combine the X and Y channels into RHC and LHC polarization in the case of circular polarization
Down-converter	Converts the RF signal into a broadband IF and/or a narrowband IF e.g. 70 MHz IF
Switching and post amplifying	Switches the different signal paths and amplifies the IF for the transmission to the main building

Depending on the type of antenna these components may be spatially separated.

FIGURE 6-29

Block diagram: Example of a feed system with tracking coupler and polarizer

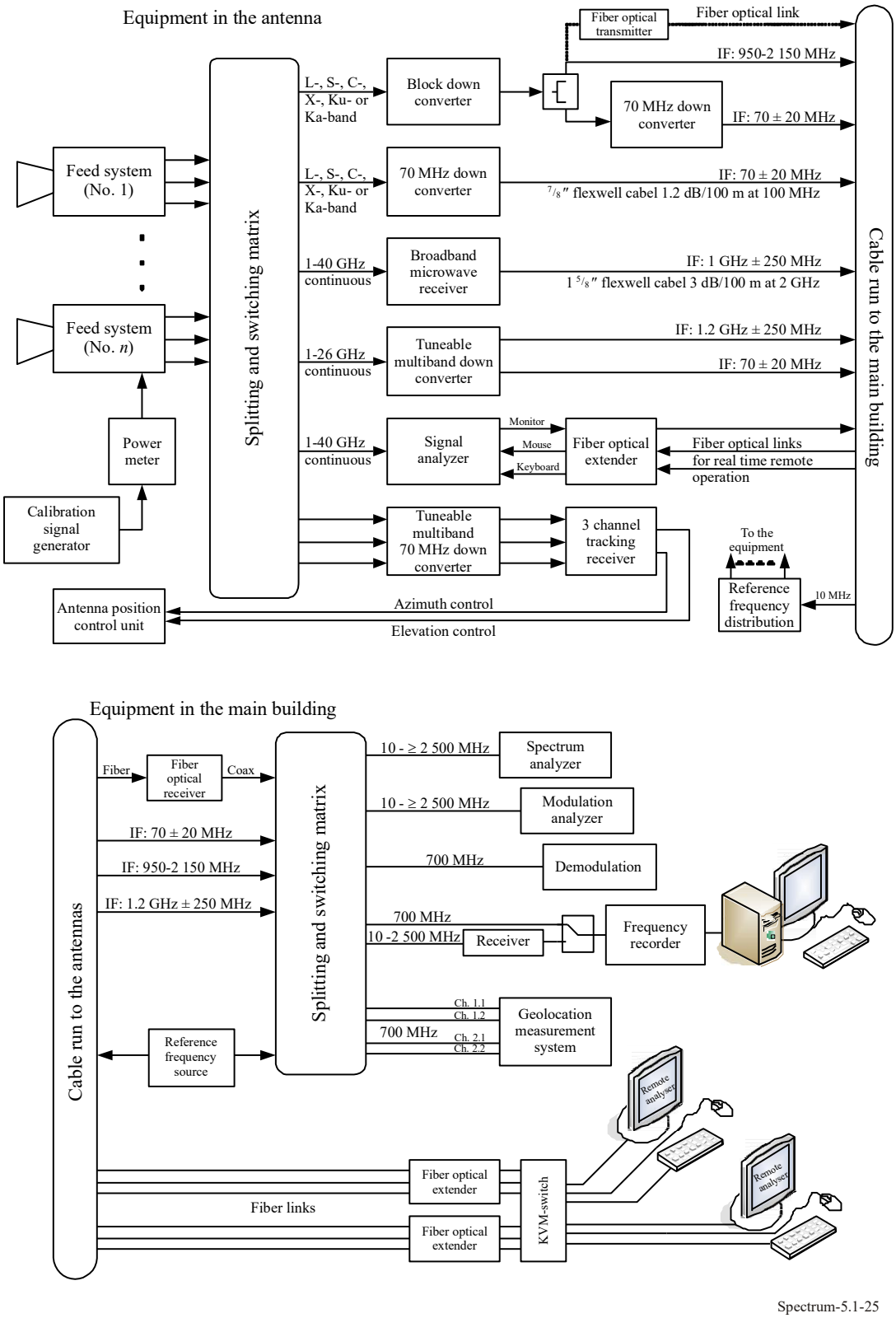


6.1.6.1.3 Monitoring equipment

The following diagrams as in Fig. 6-30 show examples for the integration of monitoring equipment.

FIGURE 6-30

Integration of monitoring equipment

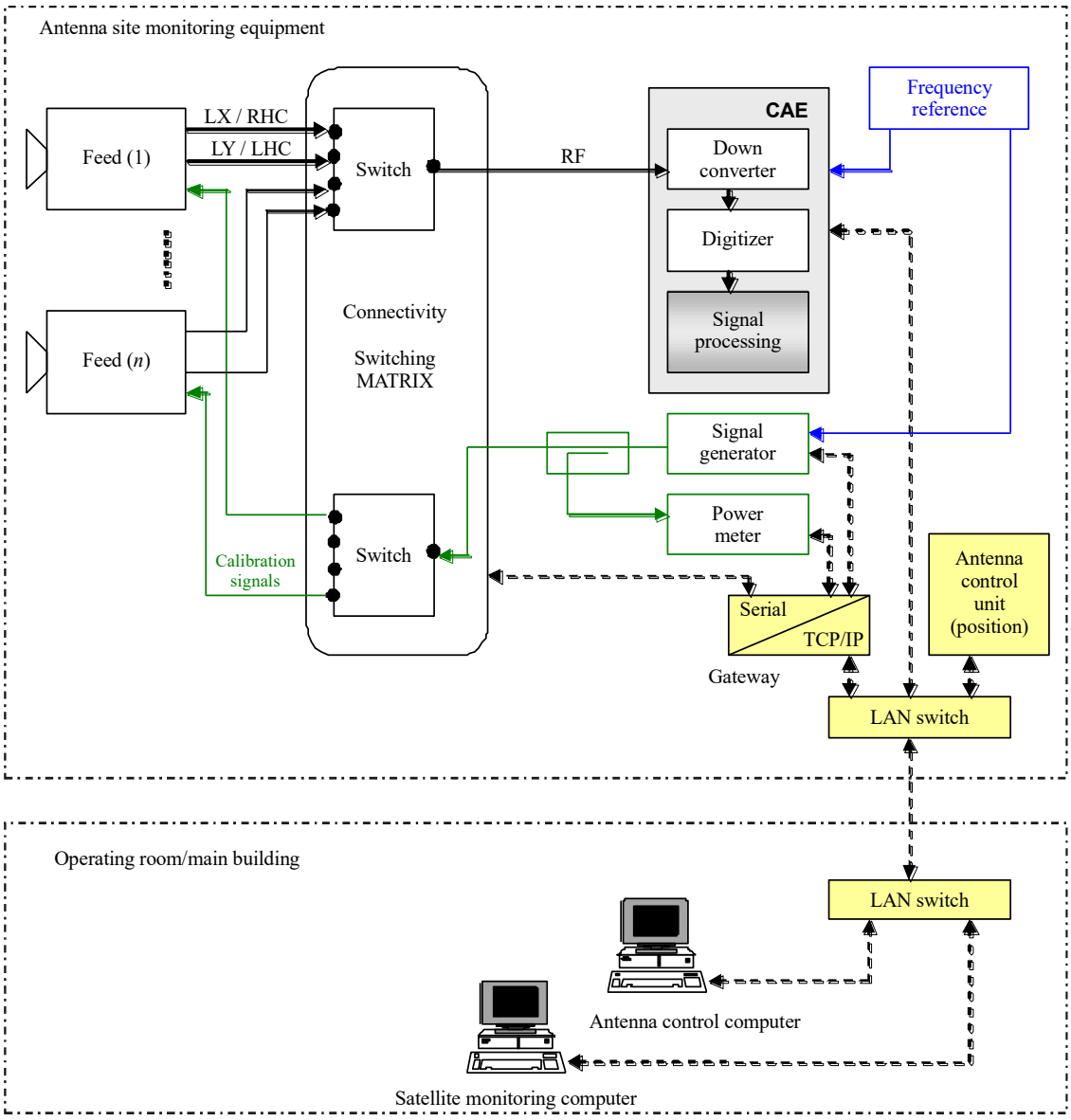


Automated satellite monitoring system

Figure 6-31 shows an automated monitoring system for carrier acquisition. The carrier acquisition equipment (CAE) hardware architecture for satellite monitoring uses a calibration system and injection points which are shown in the Figure. The power meter controls the calibration signal from the signal generator.

FIGURE 6-31

Example of an automated satellite monitoring equipment



Spectrum-5.1-26

The CAE is capable of:

– Acquiring satellite frequency in L, S, C, Ku and Ka bands.

– Detecting all carriers above noise floor (typical 6 to 10 dB above noise floor).

– Getting RF parameters for each carrier.

– Giving a full carrier classification including all digital parameters used by the modulator and the standard that is used.

The CAE shall be able to analyse and classify carriers of up to 80 MHz bandwidth which covers most of the civilian transponders.

When satellite traffic is known, the CAE detects unwanted carriers and optionally localizes the transmitters using FDOA and TDOA methods.

For the automated satellite monitoring, the following measurements should be carried out:

– RF measurements:

  - Carrier power at equipment level.
  - Carrier e.i.r.p. at satellite level.
  - Carrier C/N_0.
  - Carrier frequency by barycentre, recovery, carrier shape, peak search methods.
  - Carrier bandwidth: *x*-dB method, ß% of total power method, derived from symbol rate calculation.
  - Spectrum observations and analysis tools (markers, zoom, spectrogram, selectors).
  - Transponder e.i.r.p. at satellite level.

– Digital measurements:

  - Carrier characterization.
  - Modulation type.
  - Bit rate (transmission rate).
  - FEC rate.
  - Reed Solomon rate.
  - Standard used.
  - Carrier demodulation diagram.

– Carrier detection based on power density detection (typical 6 to 10 dB above noise floor):

  - Subsequent database update.
  - Inside defined carrier detection (carrier rejection capability shall be better than 13 dB).

– Spectrum observations, virtual spectrum observations by simulating end-user G/T.

– Fast spectrograms to visualize fast slots drifts (e.g. MF TDMA access).

– Orbital parameters (orbital position accuracy of at least ±0.1°).

– Calibration should be used to determine the gain of the reception chain.

The software system on the satellite monitoring computer should perform both interactive and automated measurements.

Interactive measurements allow the operator to investigate signals rapidly. Interactive measurements include observation of multiple bands in multiple formats, hand off signals to carrier measurements and control of the spectrum analyser and optionally receiver, tape recorder, printer and plotter.

Automated measurements should be triggered under event occurrence (see Note 1) or scheduled in background without an operator present. A task scheduling shall allow coordinating signal presence, carrier measurements, spectral occupancy and statistical measurements.

NOTE 1 – For example, an automated target signal and reference signal recording may be started immediately after unwanted signal detection. This allows paving the way for the geolocation module.

The monitoring screenshot in Fig. 6-32 showing spectrum and spectrogram information is given hereafter as an example:

FIGURE 6-32

Example of spectrum monitoring screen on the satellite monitoring computer

Spectrum-5.1-27

6.1.6.1.4 Control facilities

Operation modes of antenna control system

For the space radio monitoring an efficient control of the antennas simply to be operated is necessary. The quantity of the different operation modes should be various to point the antenna just at difficult satellites constellations efficient.

The most common antenna control functions are listed in Table 6-9.

TABLE 6-9

Operation modes of antenna control system

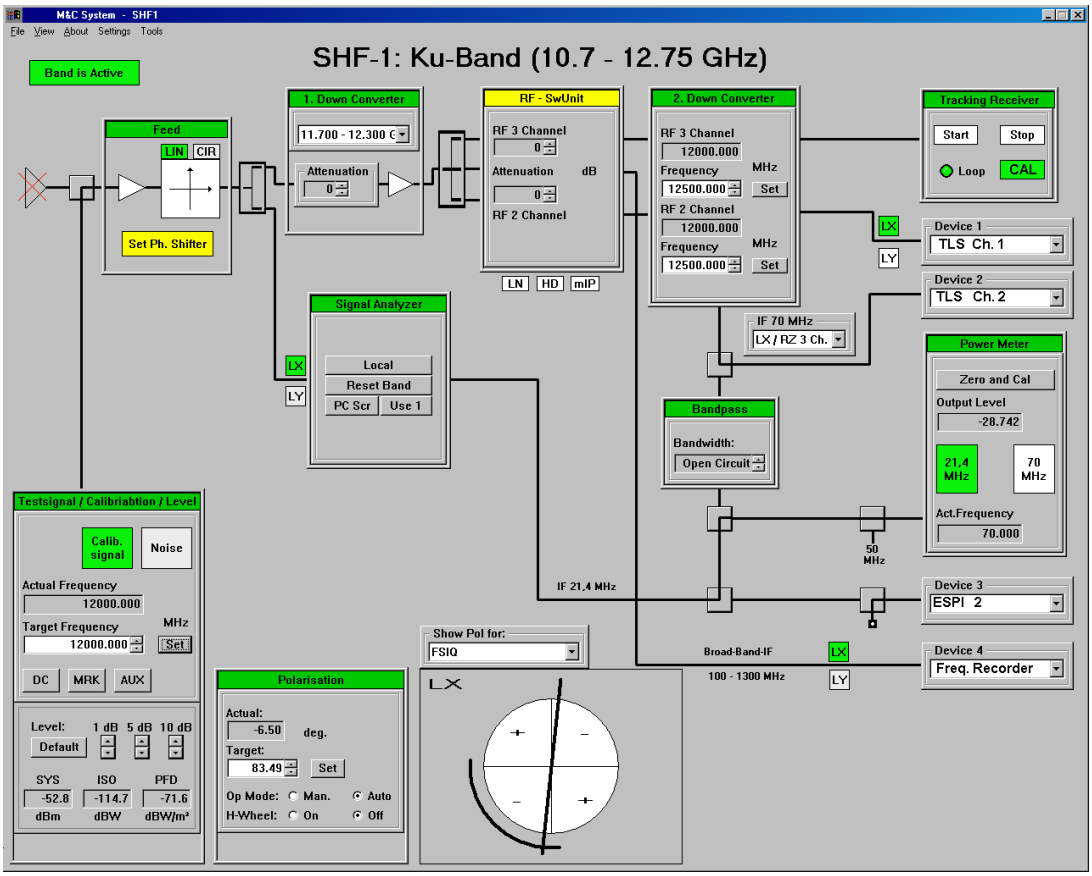
Modes	Description	Comment
PRESET	Movement to pre-defined position Input: Az and El values	
GEO PRESET	Movement to pre-defined position Input: Satellite position e.g. E19.2°	Set the antenna to a GSO orbit position without user calculation of Az and El values
POSITION	Movement at user-defined angle around the actual antenna position	Move the antenna in Az and El with 4 arrow buttons or with knobs for manual antenna adjustment
RATE	Movement at user-defined constant velocity	Most for calibration and test measurements
PROGRAM TRACK	Tracking of an object along a pre-defined path with Az, El, Date and Time data records	
TLE TRACK	Tracking of an object along a pre-defined path with TLE orbital data sets from NORAD	
STAR TRACK	Tracking of astronomical targets	Option for calibration and test measurements
AUTO TRACK	Tracking of an object using tracking error signals (monopulse tracking)	Needs a monopulse tracking coupler in the feed system and a monopulse tracking receiver
STEP TRACK	Tracking of an object using step track receiver	Needs a step track receiver but without additional components at the feed system
ORBIT PREDICTION TRACKING	Intelligent step track	Option to improve the step tracking pointing accuracy
MEMORY TRACK	Tracking using last stored satellite position data	
SECTOR SCAN	User defined sector is scanned horizontally/ vertically	Helpful to find a satellite e.g. a high inclination satellite
SEARCH SPIRAL	Pulsating spiral around last actual position	Helpful to find a satellite e.g. a high inclination satellite
GEOSYNC	Pointing to a pre-defined geo-synchronous orbit and movement on the geo arc	Manual movement with east/west buttons along the geo arc

Monitoring and control system

The monitoring and control system (M&C) is a central computer-based system for the control of all facilities in the monitoring station. A graphical user interface (GUI) represents an abstracted clearly arranged overview of the equipment and switching status on every operator's place (see Fig. 6-33 for example). For the prevention of access collisions on equipment, the system should have an assignment and locking mode. The measurement units can depend on the M&C development state and the requirements completely controlled or only for the manually use connected at the signal path of the M&C. To make an efficient workflow possible, the operation of the antenna positioning and the device control should be divided up on two monitors.

FIGURE 6-33

Example: GUI screen of a monitoring and control system (M&C)



Spectrum-5.1-28

Following equipment is controlled and inspected:

– Antenna control system for the pointing and searching functions.

– Antenna tracking system with the monopulse or the step track receivers.

– Feed system with polarization switching and polarization angle adjustment.

– Down-converters, filters and post-amplifiers.

– All switching units for connection and distribution of the RF and IF signals.

– The connection and the settings of the measurement and analytic units.

– Launching automated measurement software.

In Fig. 6-34, signals 1.1 and 1.2 received by the antenna 1 from the interfered satellite. Signals 2.1 and 2.2 received by antenna 2 from the adjacent satellite. Signals 1.1 and 2.1 are the interferer signals, 1.2 and 2.2 are the reference signals.

FIGURE 6-34

Principle: Geolocation measurement system

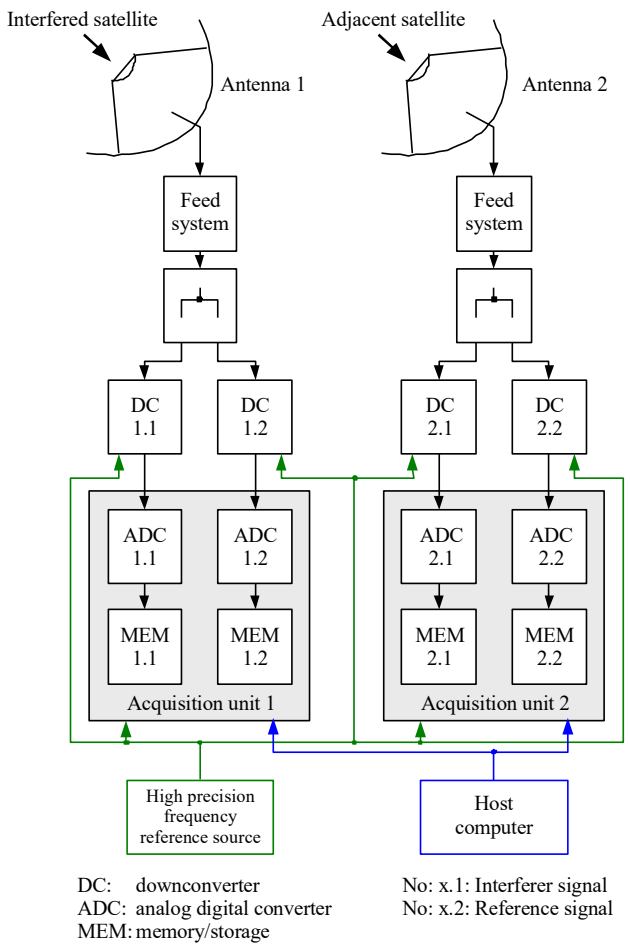
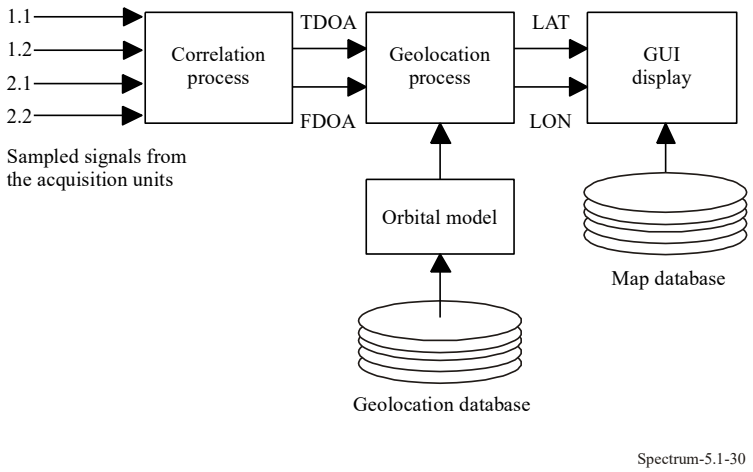


FIGURE 6-35

Principle of geolocation calculation procedure in the host computer



6.1.6.2 Process for radio monitoring of GSO satellites

An automated system for radio monitoring of GSO satellites is described below. It attempts to minimize the number of operators in its task of measuring the orbit and radio wave quality using various techniques.

The automated monitoring system is equipped with a computer program which has the following managing functions:

– Control, for the establishment of operation priority.

– Registration, for the scheduling of a single measurement.

– Error detection of the system software with a reporting function to operators.

– Searching and measuring.

– Calibration of the system and inspection to check whether the monitoring facility operates properly.

– Reporting for measurement result to the operators.

– Storing of the registered satellites and the measurement results in the database.

Operators of the space radio monitoring station should construct the monitoring schedule so that monitoring tasks are routinely performed according to the monitoring plan.

For detecting harmful interference sources, monitoring new satellites and measuring the frequency spectrum occupancy in detail, the semi-automatic and manual modes may well operate simultaneously.

The specified items in the monitoring schedule include such items as monitoring time, automatic or semi-automatic mode selection, satellite name, number of times for monitoring, task priority.

Figure 6-36 shows the example of the sequential process of monitoring.

Measurement items of the scheduling process include satellite orbital position, polarization, centre frequency, pfd, occupied bandwidth and so on. It is important for space radio monitoring facilities to have techniques for fast tracking, choosing polarization by means of comparison algorithms, locating centre frequencies for measuring occupied bandwidth, and measuring carrier power.

The polarization is determined by repeatedly checking incoming measurements against the polarization criteria.

Usually, the mono-pulse tracking method is chosen but other methods such as step tracking are also used.

Satellite identification is verified by comparing measurement result with the satellite database.

Repetition of measurement and corrections are required in order to improve the accuracy and reliability of the measurement results.

Such a measurement task should be performed with high reliability considering the propagation characteristics at the high frequency and the weak signal of the satellite received on the Earth. The monitoring stations verify whether the satellite is operated following the technical standards and regulations.

Moreover, operators register or renew the operation schedule for any new monitoring request and special task. Storing of the standard procedures which are often used will simplify the registration process.

6.1.6.3 Precise orbital longitude monitoring (radio interferometry)

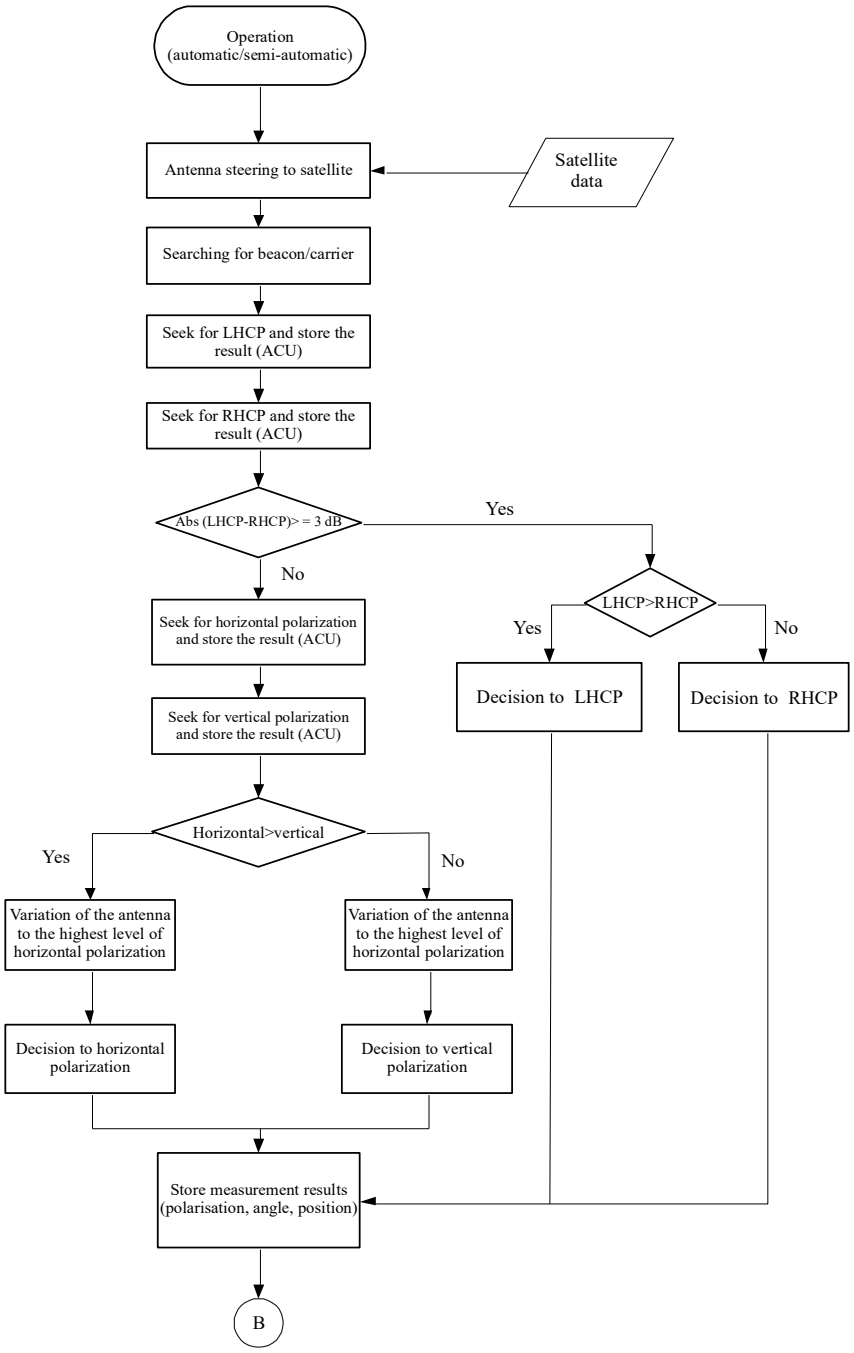
6.1.6.3.1 Purposes of precise orbit monitoring

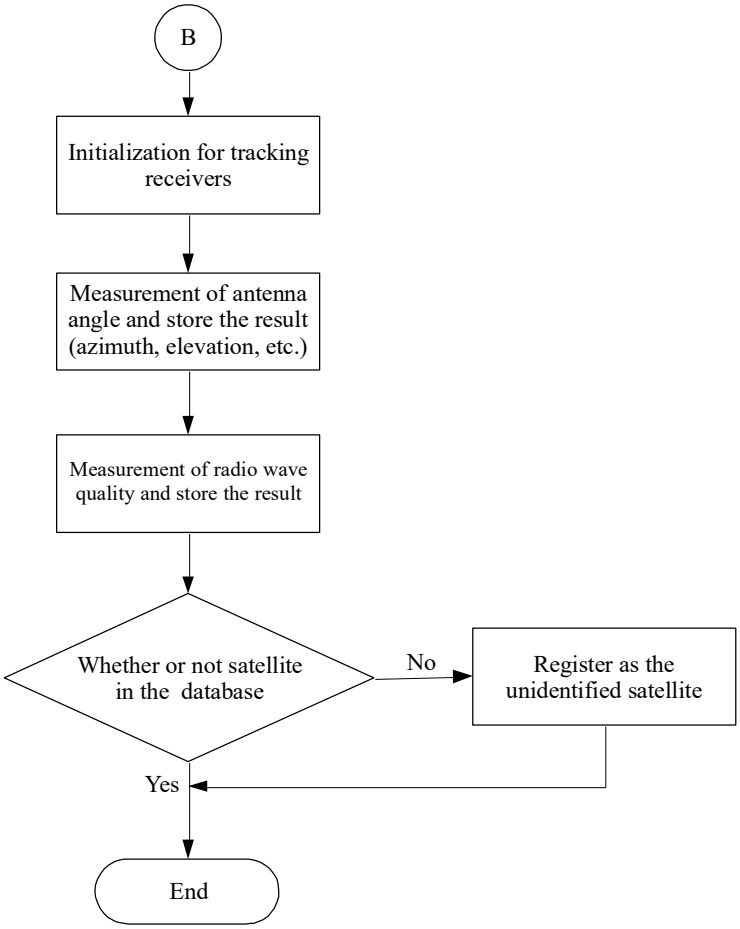
There is a growing demand for precise orbit monitoring owing to the ever increasing number of satellites in geosynchronous orbits. Strict station-keeping is necessary for satellites located at orbital longitudes that are close to each other, without which the satellites may come too close to one another. Accordingly, the precision in orbit monitoring must be more than the conventional ±0.1°.

In some cases, two or more satellites are located at the same orbital longitude. In such a case, the orbital slot of ±0.1° is divided into sub-slots, and each satellite is allotted a unique sub-slot. Monitoring in such cases must be even more precise.

FIGURE 6-36

Sequential process of monitoring





Spectrum-5.1-31-cont

Precise orbit monitoring is also essential in the geolocation of transmitters, since geolocation relies on accurate information regarding the six orbital elements of satellites. A monitoring station that operates transmitter geolocation should preferably be capable of generating orbital information by receiving satellite down-links.

There is thus a growing need for precise orbit monitoring of geosynchronous satellites. A promising technique that can be used for this purpose is radio interferometry. An example of a radio interferometer with its technical specifications and operation procedure is presented in the following sections.

6.1.6.3.2 Interferometer hardware

An interferometer is basically a system comprising two receiving antennas for measuring phase differences, while an actual orbit-monitoring interferometer takes the form shown in Fig. 6-37. The down-link microwave from a target satellite is first reflected by mirror A and then by mirror B, before being received by antenna C. The mirrors are planar. Similarly, the microwave is reflected by mirrors D and E, before being received by antenna F.

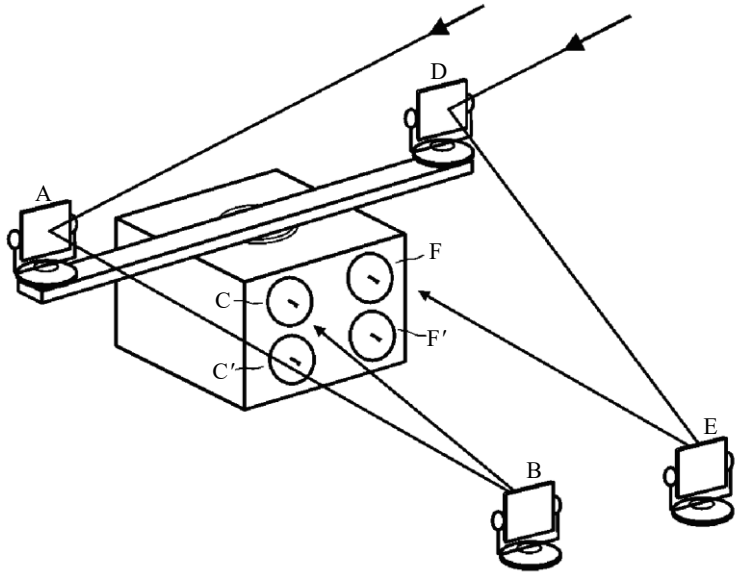
The phase differences between antennas C and F are measured. After correcting for the phase delays over paths A-B-C and D-E-F, one can assume that the receiving antennas are at A and D. Line AD then becomes the DF baseline of the interferometer.

Mirrors A and D are positioned on a horizontal rotary arm, for reasons shown later. As the arm changes its orientation, the mirrors are repointed so that the microwaves are accurately guided to the receiving antennas. The two pairs of antennas (C, F and C′, F′) are used for two different frequency bands. Mirrors B and E are tilted to choose the desired pair of antennas.

FIGURE 6-37

Radio-interferometer for geosynchronous orbit monitoring

A, B, D, E: planar mirrors; C, F, C′, F′: fixed antennas



Spectrum-5.1-32

Figure 6-38 illustrates the measurement of phase difference between the antennas for a given frequency band. In each receiving route, signals are down-converted before being input to FFT. The down converters are phase-synchronized by using local signals from a common oscillator (LO). The Fourier-transformed data are then cross-multiplied and time-integrated; this process is referred to as correlation processing. Since noises are suppressed by time-integration, the phases are measured with an improved *S*/*N*, and this is equivalent to improving the receiving antenna's *G*/*T*.

The correlation processor has a bandwidth of 20 MHz, and any signal within this bandwidth – beacon or band-pass communication signals – can be chosen as the measuring target. Reference signals from a common oscillator (RO) are coupled into the low-noise amplifiers, in order to compensate for phase variations that can occur in the receiving routes.

The specifications of the interferometer are listed in Table 6-10. The fixed antennas and rotary arm with mirrors appear as in Fig. 6-39. Other mirrors, which appear as in Fig. 6-40, are 16 m away from the fixed antennas. Presently, the interferometer has two frequency bands, and a new band can be added by placing another pair of receiving antennas and down-converters.

The receiving equipment shown in Fig. 6-38 uses conventional earth-station antennas and components, while the correlation processor is specific to this interferometer.

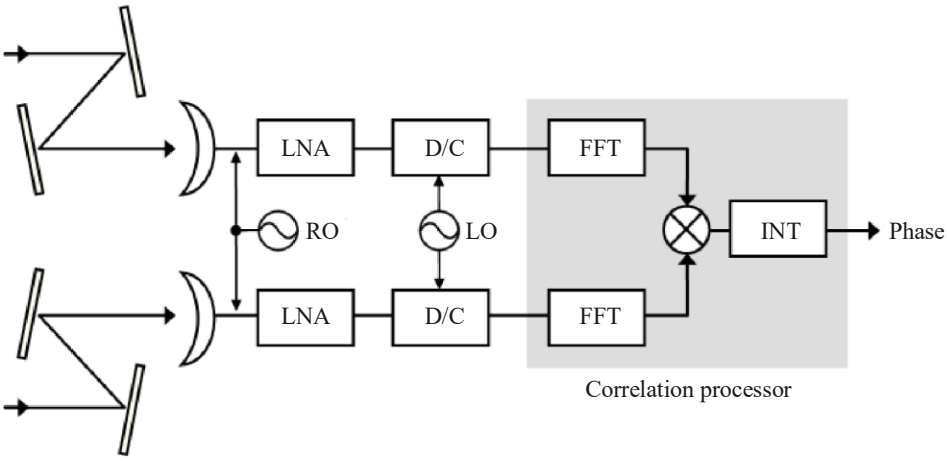
If the interferometer were designed so as to mount the receiving antennas on the arm at A and D in Fig. 6-37, the cables between the antennas and the in-house units would twist as the arm rotates, thus causing phase errors.

The use of guiding mirrors enables the placement of antennas C and F (and C′ and F′) side by side; hence, the lengths of the cables can be sufficiently shortened to ensure phase stability when the surrounding temperature changes. In addition, mirrors B and E are useful for band switching. The arm and the mirrors can balance weights around their rotary pivots owing to their symmetric forms. Therefore, small motors can drive them smoothly.

FIGURE 6-38

Block diagram for phase-difference measurement

LNA: low-noise amplifier; D/C: down-converter; FFT: fast Fourier transform
RO: reference oscillator; local oscillator; INT: time-integration



Spectrum-5.1-33

FIGURE 6-39

Rotary arm, planar mirrors and fixed antennas (upper: Ku-band, lower: C-band)

Spectrum-5.1-34

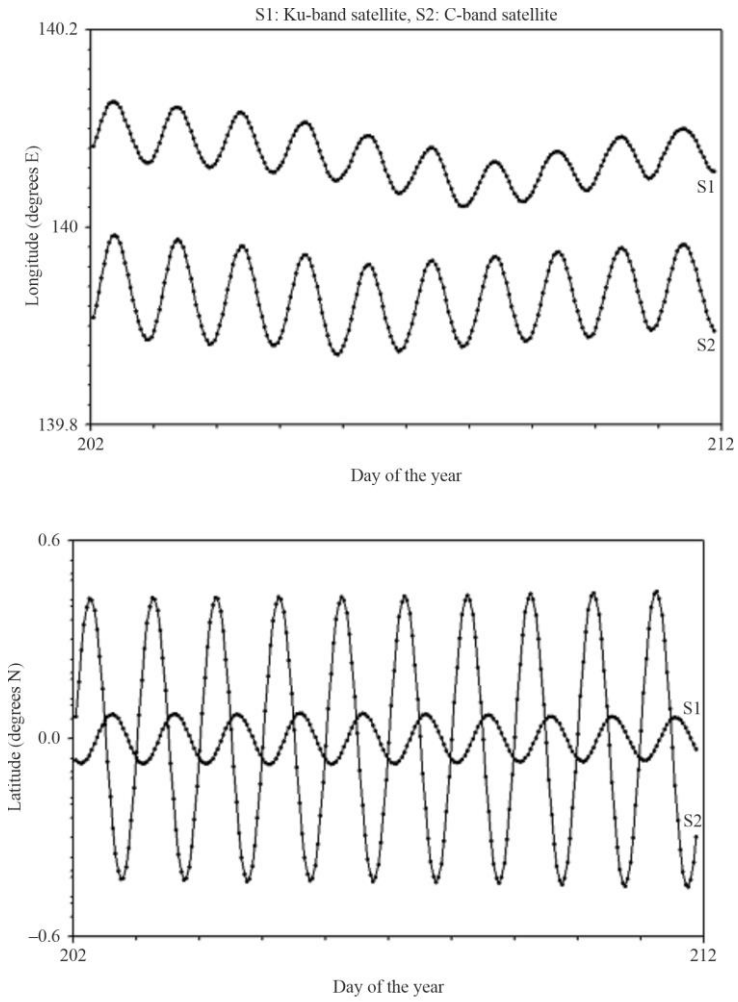
FIGURE 6-40

Planar mirrors for band switching

Spectrum-5.1-35

FIGURE 6-41

Example of satellite position monitoring



HDB23-6-41

6.1.6.3.3 Interferometer operations

The interferometer operates in different modes for different monitoring purposes, as listed in Table 6-11.

The rotary mode is a start-up procedure for monitoring an unknown satellite. The arm goes through one revolution while stopping at every 15° of the orientation angle. Each time when the arm is at rest, phase data are collected. One round of data collection takes 15 min for one satellite. The phase data are then processed, to determine the satellite direction in azimuth and elevation. The rotary mode is essential for resolving phase ambiguity. If x is a phase measured in degrees, then it may also be equivalent to $x \pm 360$, $x \pm 720$, etc. Collecting phase data at different arm angles allows unambiguous determination of the satellite direction.

At the end of the rotary mode, monitoring of the same satellite can be continued in the quick mode. Phase data are collected, every hour, at two different arm orientation angles that differ by 90°. The data are recurrently input to an orbit estimation program from which satellite positions in longitude and latitude are output.

An example of this type of position monitoring is shown in Fig. 6-41, where two satellites operate in adjoining longitudes. Parallel monitoring of three or even more satellites is also possible, since one set of data collection for one satellite finishes in a few minutes. Six orbital elements can be also output if input data are sufficient. Data collection must be carried out at least for half a day, while it must be for one day for obtaining good orbital elements.

The fixed mode is used for monitoring satellite longitudes. The arm is oriented east-west and fixed at this position, while its precise angle depends on the location of the target satellite. Phase data are converted to satellite longitudes through a linear mapping function.

Prior to the fixed mode, the rotary mode must be carried out for starting up. The fixed mode is useful for monitoring long-term longitude occupancy of satellites.

6.1.6.3.4 Error calibration

Since the interferometer has movable components, mechanical positioning errors are inevitable. Major errors are modelled by the following parameters:

– Effective length of the arm.
– Bias in the arm orientation angle.
– Off-horizontal tilt of the arm for east-west orientation.
– Off-horizontal tilt of the arm for north-south orientation.

To calibrate the error parameters, five satellites at different orbital locations are chosen as references. The azimuth and elevation of the reference satellites are assumed to be known. The error parameters are then adjusted, so that the azimuth/elevation data from the interferometer agree with the reference data.

The errors are calibrated annually to maintain the accuracy according to the level specified in Table 6-10.

TABLE 6-10

Interferometer specifications

Frequency band	C: 3 400-4 200 MHz Ku: 11 700-12 750 MHz
Fixed antennas	Diameter: 1.8 m *G*/*T*: 16.8 dB/K (C) *G*/*T*: 23.2 dB/K (Ku)
Rotary arm	Length: 13 m Pointing precision: 0.001°
Planar mirrors	Square with a side of 2 m Pointing precision: 0.01°
Correlation processor	Bandwidth: 20 MHz Target signal: beacon or band-pass *S*/*N* improvement: 23 dB (1s-integration)
Direction-finding accuracy	0.005°

TABLE 6-11

Interferometer operation modes

Rotary mode	Arm rotates through one revolution Determines azimuth-elevation direction Starting up for quick mode/fixed mode
Quick mode	Arm rotates between two orientation angles Outputs longitude-latitude position Outputs six orbital elements
Fixed mode	Arm is fixed at east-west Outputs satellite longitude

6.1.7 Monitoring results by examples

6.1.7.1 Frequency band recording

Radio frequency spectrum recording systems are especially suitable for the monitoring of frequency bands for occupancy by emissions from low orbiting space stations.

The structure of the occupancy pattern (Doppler curve) depends on the orbital elements of the satellite and is of fingerprint quality.

In addition to the receive frequency, the period of revolution (PERIOD raw), taken as the average of several consecutive revolutions, and the expected times of reception may be different. In order to determine the period of revolution with a satisfactory degree of accuracy (PERIOD fine) an iterative method is recommended using registrations taken over a period of several days on the basis of equations:

$$PERIODraw = T2 - T1 \tag{6-20}$$

$$PERIODfine = (Tx - T1)/n \tag{6-21}$$

Tx is the centre point of the receiving window one day or several days later. The divisor, *n*, is a fictitious number of revolutions in the case of equation (6-21).

It is systematically altered until the minimum divergence between the desired result for the *PERIOD* fine and *PERIOD* raw is achieved. In this way, the measurement error of the time of revolution may be reduced after a period of only 24 h to some tenths of a minute. The time of revolution and the characteristics of the recording pattern are reliable for the identification of a satellite.

Another method is the use of an adjustable time line grid as an overlay in the spectrogram of the recorded satellite emissions over a period of two or more days. If the time lines match the satellite emissions the PERIOD raw is found. In the example as shown in Fig. 6-42, the PERIOD raw is 112 min.

To find out the exact period time, the search in an information database of existing satellites is necessary as a second step.

With the result of a PERIOD raw of 112 min, satellites with a revolution period close to 112 min can be searched. Figure 6-43 illustrates an example of information database with marked satellites close to 112 minute-periods.

With the related two-line elements the visibility time for these satellites for the location of the monitoring station have to calculate.

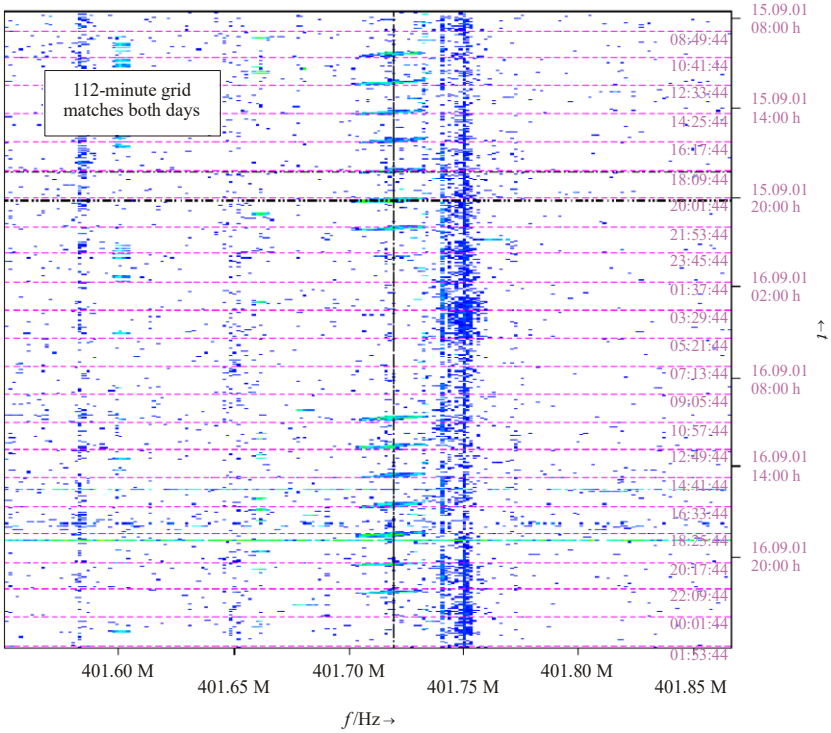
The frequency recorder system can display these visibility windows as an overlay in the spectrogram of the received satellite emission.

If the visibility windows match all the recorded satellite emissions the satellite is identified. Figure 6-44 illustrates the visibility windows for the S80/T satellite with a revolution period of 111.9 min.

After the orbit data are known now, with these data a directional antenna can track the satellite for further measurements.

FIGURE 6-42

Frequency occupancy registration, approximated determination of time of revolution



Spectrum-5.1-37

FIGURE 6-43

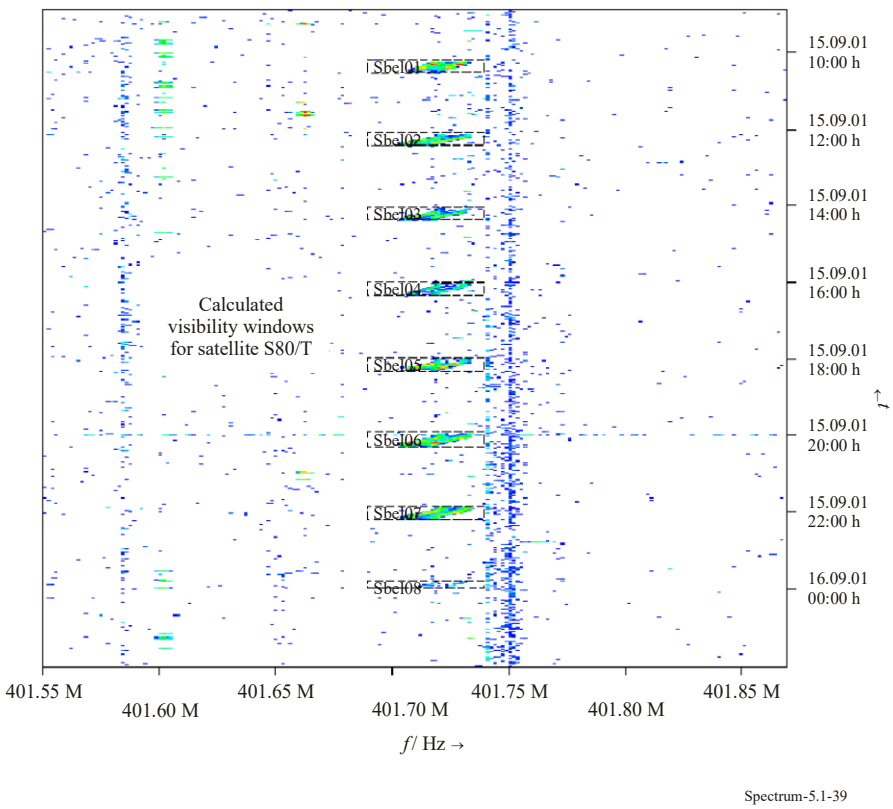
Search in an information database

INT-ID	CAT	SRC	PERIOD	INCL	APOG.	PERIG.	RCS	NAME	DATE
1990-114F	21033	CIS	113,7	82,6	1410	1386	2,2032	COSMOS 2119	22.12.90
1989-074B	20233	CIS	113,7	82,6	1410	1386	1,7514	COSMOS 2039	14.09.89
1988-002F	18793	CIS	113,7	82,6	1411	1384	1,9042	COSMOS 1914	15.01.88
1987-074A	18334	CIS	113,7	82,6	1409	1387	2,1058	COSMOS 1875	07.09.87
1987-026B	17583	CIS	113,7	82,6	1411	1385	2,2787	COSMOS 1828	13.03.87
1985-003C	15471	CIS	113,7	82,6	1413	1383	1,3662	COSMOS 1619	15.01.85
1992-052A	22076	US	112,4	66	1344	1332	10,6361	TOPEX/POSEIDON	10.08.92
1990-013C	20480	JPN	112,2	99,1	1744	912	0,3319	JAS 1B (FUJI 2)	07.02.90
1990-013B	20479	JPN	112,2	99,1	1743	912	0,4893	DEBUT (ORIZURU)	07.02.90
1992-052C	22078	FR	111,9	66,1	1325	1305	0,4416	S80/T	10.08.92
1992-052B	22077	KOR	111,9	66,1	1325	1307	0,2912	OSCAR 23 (KITSAT 1)	10.08.92
1994-046A	23191	US	110,6	70	2156	355	3,8606	APEX	03.08.94
2000-075C	26621	SWED	110,5	95,4	1799	701	0,1528	MUNIN	21.11.00
1989-086A	20305	CIS	110,4	82,6	1251	1238	11,6301	METEOR 3-3	24.10.89
1995-059B	23711	US	109,7	100,5	1493	934	13,2018	SURFSAT	04.11.95
1994-003B	22970	GER	109,4	82,6	1208	1185	7,6481	TUBSAT B	25.01.94
1994-003A	22969	CIS	109,4	82,6	1208	1186	41,1628	METEOR 3-6	25.01.94
1991-030A	21232	CIS	109,4	82,6	1208	1188	9,5992	METEOR 3-4	24.04.91
1991-056A	21655	CIS	109,3	82,6	1206	1187	7,8738	METEOR 3-5	15.08.91
1988-064A	19336	CIS	109,3	82,5	1208	1184	8,0195	METEOR 3-2	26.07.88

Spectrum-5.1-38

FIGURE 6-44

Visibility windows in the frequency occupancy registration



6.1.7.2 Calculation of orbital elements from antenna angle measurements

The identification of a satellite is made easier, and in some cases only possible, by the use of orbital elements calculated from antenna angle measurements. The question of whether or not a sufficiently accurate determination may be obtained depends largely on the angle measurement accuracy of the antenna available and the length and type of the tracked orbit arc. The following example should allow specific conclusions to be drawn regarding the achievable calculation accuracy, which may not at the same time be universally applicable. It is based on a comparison between the ephemeris data of the space station NOAA10, published with a good degree of accuracy and therefore used as reference data, with the ephemeris data obtained from antenna angle measurements and on a comparison between the visibility times and the azimuth and elevation calculated on the basis of both sets of ephemeris data for a path approximately 24 h later.

The antenna angle measurement accuracy of the available 12 m parabolic reflector antenna using the monopulse technique is approximately 0.12° in the 1 700 MHz frequency band used (see also § 6.1.3.5). The maximum elevation angle of the tracked orbit above the horizontal plane was approximately 60°.

Three sets of antenna angle measurement data (azimuth/elevation/time) are used for an initial mathematical determination of the orbit, followed by calculation of the orbital elements. In order to improve the results, a parametric calculation is then made, with the aim of obtaining a solution, which corresponds as closely as possible to the antenna angle measurement values for the series of measurements. [Montenbruck, 1989]; [Montenbruck and Pfleger, 1991].

Table 6-12 and Fig. 6-45 illustrate the results of these comparisons. When used as an identification aid, the elements in Table 6-12 can considerably facilitate the identification of a satellite. However, when the ephemeris data as a whole are used for the predetermination of azimuth and elevation as a function of time, deviations growing with interval to the epoch are observed. Limitations in accuracy when computing the orbital elements from the angle measurements of a single satellite path only are the reason for this. The satellite pick up during the following paths however is remarkably improved. The divergence of azimuth and elevation for a satellite path 24 h later (after 14 revolutions) and based on initial orbit determination is presented in Fig. 6-45. The calculated curves are shifted by –1 min for compensation of time delay.

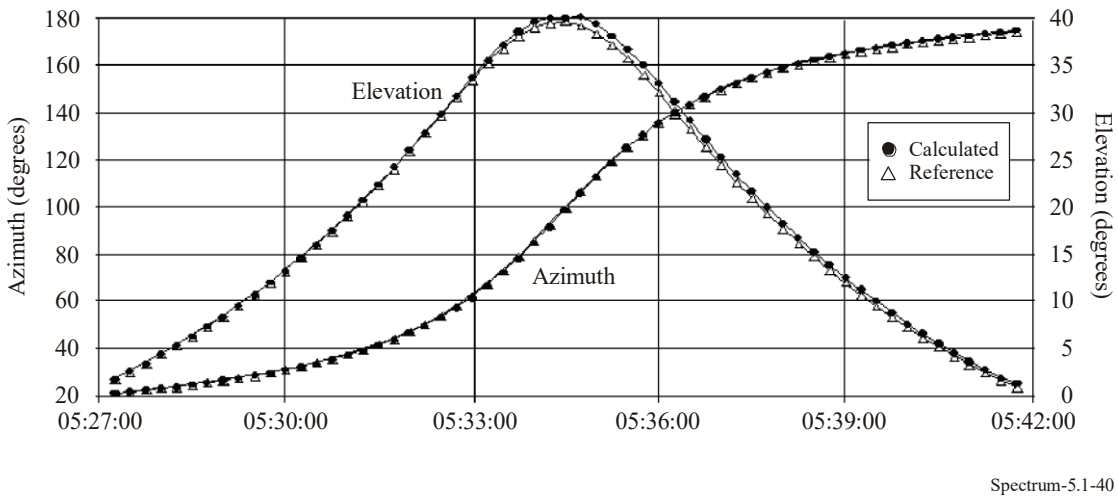
TABLE 6-12

Comparison between reference orbital elements and computed orbital elements (initial orbit determination)

Orbital elements NOAA10	**Reference elements**	**Computed elements**
Perigee (km)	807	808
Apogee (km)	825	830
Semi-major axis (km)	7 187	7 190
Eccentricity	0.0012156	0.0015
Inclination (degrees)	98.5121	98.78
Time of revolution (min)	100.781	100.85

FIGURE 6-45

Comparisons between antenna angles computed from reference orbital elements and from measured orbital elements



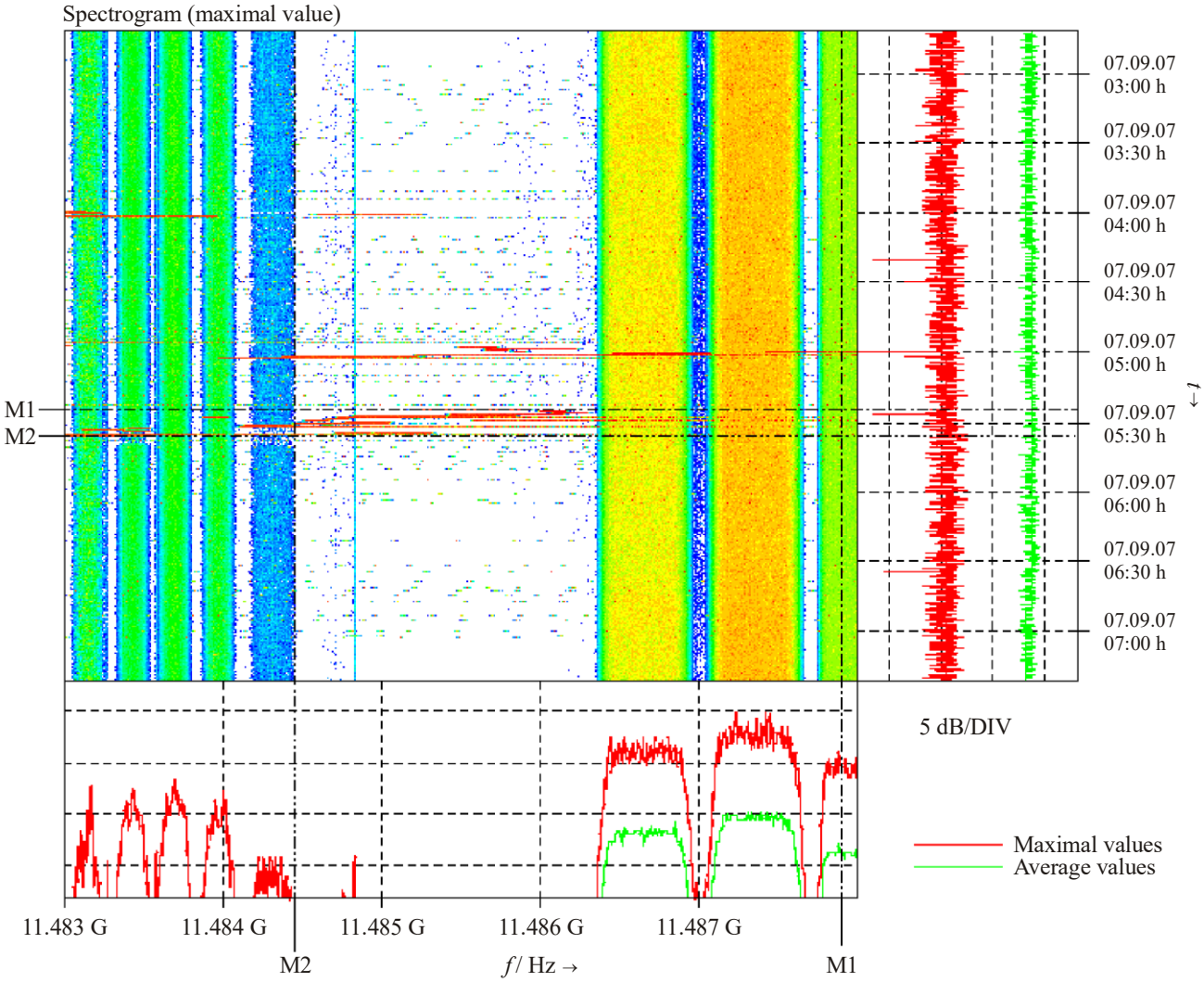
6.1.7.3 Transponder occupancy measurements

Figure 6-46 illustrates the result obtained from a transponder occupancy measurement with a frequency recording system. The spectrogram shows a satellite transponder occupancy with an unused transponder section in the middle of the displayed frequency range and a temporarily appearing high power interfering signal. The interferer is crossing the whole transponder fast up and down. The signal, received with a directional antenna, is connected to the frequency recorder in the IF range. The signal is digitized and on-line represented with a FFT transformation as a spectrogram in the frequency recorder. The spectra are stored continuously on a hard disk and are available for the further offline processing. The different colours represent the power level in the spectrogram. The displayed power level range is adjustable by the colour range settings. The spectrogram can be changed in the frequency range and in the recorded time range by zooming in so that

a short observation period can be represented very in detail or zooming out for a long observation period provides a general view. To the position of the frequency marker line and the time marker line is on the right side and below the spectrogram displayed the respectively spectrum.

FIGURE 6-46

Transponder occupancy measurements



	Level	Frequency	Time	Samples	Dead T.
M1	–65.0 dBm	11.487915 GHz	05:23:50 h	399	40 ms
M2	–81.0 dBm	11.484453 GHz	05:35:15 h	399	30 ms
Δ	16.0 dB	3.4614 MHz	–00:11:25 h		

Marker 1
Marker 2

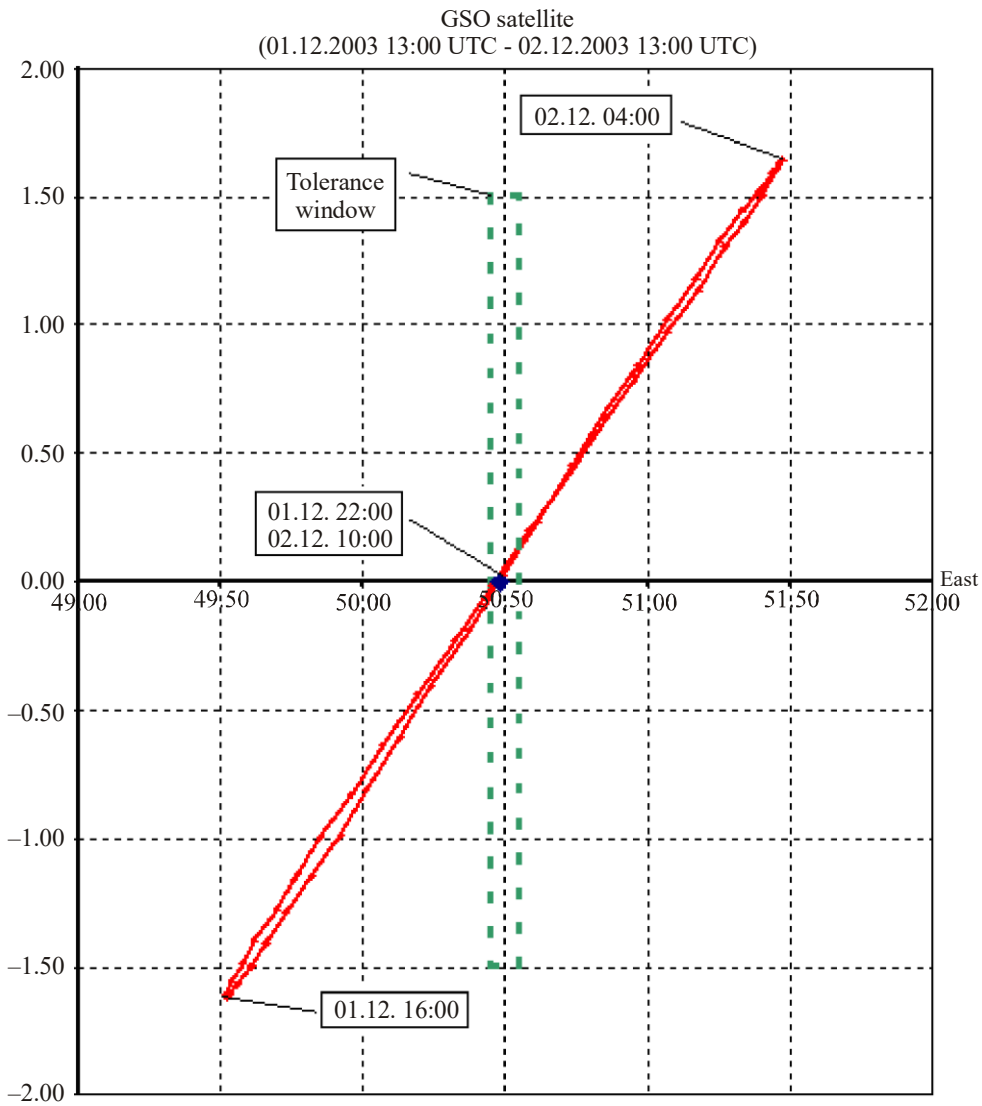
Spectrum-5.1-41

6.1.7.4 Inclination of GSO satellites

The plot in Fig. 6-47 was obtained by observing the position of a GSO satellite at 30 min intervals by using a 12 m parabolic antenna with a half-power beamwidth of 0.15°. Based on a monopulse tracking procedure the antenna pointing data are acquired automatically by initially manually locating the satellite. The satellite positions are recorded over a 24 h period and the results are calculated to produce the figure "8". The information obtained shows the satellite's excursion from its nominal orbital position and provides a reference for future observations.

FIGURE 6-47

Inclination of geostationary satellites (Fig. "8")



Spectrum-5.1-42

6.1.7.5 Result and presentation of a geolocation measurement

Figure 6-48 presents the results obtained from a TDOA and FDOA geolocation measurement of an unknown uplinking earth station. The result is usually presented in the form of an elliptical area, which can be overlaid on a digital map application for better understanding. The shape and the orientation of the ellipse may vary significantly due to the number of measurement made, the measurement time of the day, modulation type of the signal under test, the correlation SNR etc.

The factors to define the ellipse include:

– The length of the semi-major axis.

– The length of the semi-minor axis.

– Angle of semi-major axis (or semi-minor axis) with respect to a reference direction.

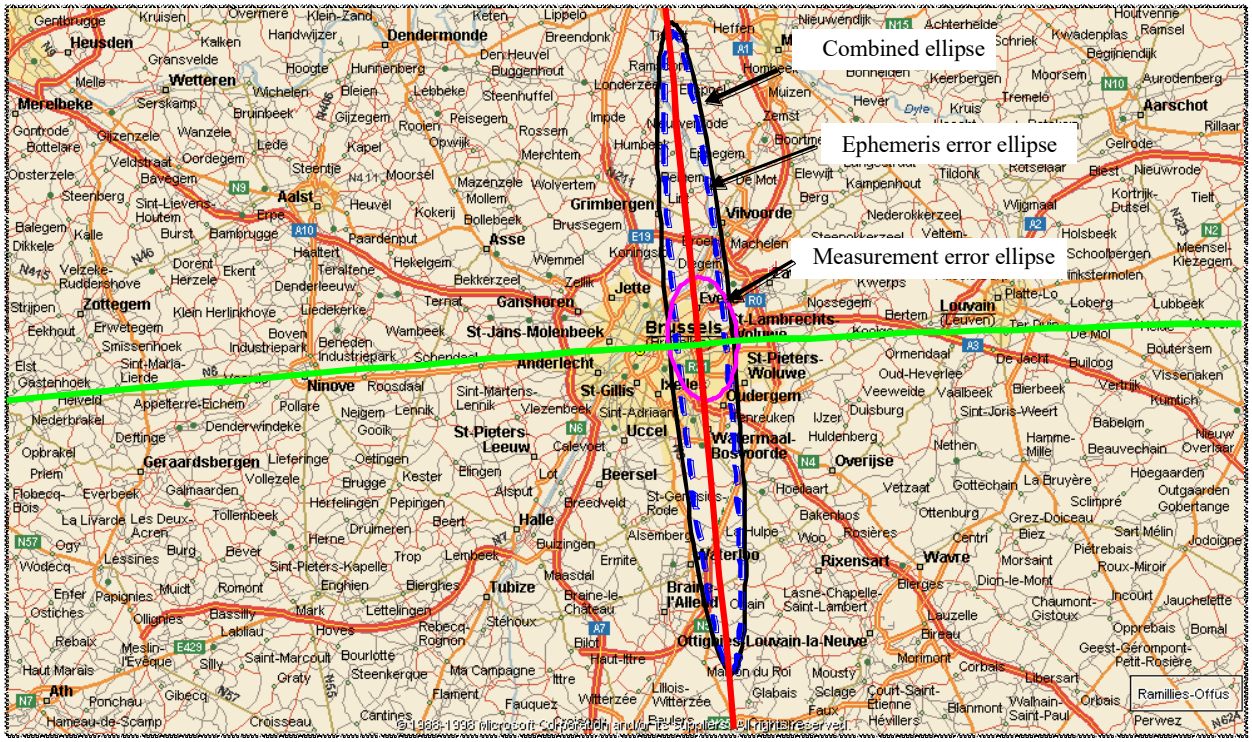
– Coordination of the centre.

– Confidence level.

Shown below is the representation of a geolocation measurement on map with the error ellipse. The huge ellipse for the ephemeris error shows inaccuracies in satellite position and velocities. In this case an ephemeris error compensation measurement should be carried out.

FIGURE 6-48

Geolocation result of earth station transmitting to GSO satellite



Spectrum-5.1-43

6.1.8 References

NOTE – In every case the latest edition of the ITU Radio Regulations, ITU-R Recommendations and ITU-R Reports should be used.

ITU Radio Regulations

ITU-R Recommendations and Reports

Recommendation ITU-R F.699 – *Reference radiation patterns for fixed wireless system antennas for use in coordination studies and interference assessment in the frequency range from 100 MHz to 86 GHz*

Recommendation ITU-R S.673 – *Terms and definitions relating to space radiocommunications*

Recommendation ITU-R S.1503 – *Functional description to be used in developing software tools for determining conformity of non-geostationary-satellite orbit fixed-satellite service systems or networks with limits contained in Article 22 of the Radio Regulations*

Recommendation ITU-R SM.1681 – *Measuring of low-level emissions from space stations at monitoring earth stations using noise reduction techniques*

Recommendation ITU-R SM.2117 – *Data format definition for exchanging stored I/Q data for the purpose of spectrum monitoring*

Recommendation ITU-R SM.2149 – *Guidance on supplementary elements on the use of Appendix 10 of the Radio Regulations to convey information related to harmful interference to space radiocommunication services*

Report ITU-R SM.2424 – *Measurement techniques and new technologies for satellite monitoring*.

External References

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6.2 Monitoring of terrestrial broadcast emissions

6.2.1 Introduction

One could consider that broadcasting services, radio and TV are adequately covered by the standard monitoring procedures. Particularly when it comes to a means for mass communication and, as such, as a tool for education and to promote regional and national cultural values. Whilst the procedures discussed in the previous chapters cover most of the basic measurements performed on broadcasting services, several countries apply their own notable regulations and content restrictions on a national basis to these services including:

– coverage areas;

– quality of service;

– time limits on advertising;

– minimum amount of cultural, educational, or current affairs programs, etc.

These regulatory constraints will demand specific monitoring procedures and equipment. Although standard monitoring receivers usually have demodulation capabilities that allow the reception and recording of broadcast programs, the use of expensive measurement instruments in such a menial task is economically inefficient and inadequate since the reception characteristics might not be suitable in terms of quality. For example, some monitoring receivers are unable to record stereo channels or present the decoded picture itself. Most of the time, measurement instruments will not provide a good correlation in terms of performance, selectivity and quality to consumer products specifically designed to be used to access these services.

Based on these concepts, this subchapter will present general guidelines to expand the monitoring facilities by implementing additional monitoring channels adequate to content monitoring. These subsystems usually are essential to perform activities such as coverage and quality of service evaluation, providing receiving characteristics closer to the final user experience. They also may prove invaluable to provide the ability to simultaneously monitor multiple channels at relatively low cost.

Considering the spectrum usage, broadcasting services, especially FM sound broadcasting and TV broadcasting, usually apply high transmission power over large segments of the spectrum at VHF and low UHF. This is very close to critical applications such as aeronautical navigation and communication frequencies, increasing the importance of a tight control over unwanted emissions and, as such, the importance of monitoring activities as a means to prevent interference to other services. On this subject, this chapter will briefly present the characteristics of main broadcast standards in use, providing a reference for the analysis of these systems.

6.2.1.1 Frequencies allocated to the terrestrial broadcasting service

According to the ITU Radio Regulations, there are different bands allocated to the broadcasting service: part of LF, MF and HF bands are used for sound broadcasting and the VHF and UHF bands are used for sound and television broadcasting (see ITU webpage Frequency Bands allocated to Terrestrial Broadcasting Services).

The channel bandwidth depends on the choice of the broadcasting system and, for example, for television it is mainly 6, 7 or 8 MHz.

It is also important to notice that there are many regional plans that govern the utilization of these bands (see ITU webpages on *LF/MF Regional Frequency Assignment Plans* and *FM/TV Regional Frequency Assignment Plans*).

6.2.1.2 Quality of service

Quality of service is defined as the collective effect of service performance which determines the degree of satisfaction of a user of the service (see *ITU Terms and Definitions*).

In general, one can consider three methods of quality evaluation applicable for broadcasting and telecommunications in general:

1) *Intrinsic quality*, where technical parameters of the service are considered, for example, signal to noise ratio (SNR), signal to interference ratio (SIR), signal to interference plus noise ratio (SINR), Total Harmonic Distortion (THD), relative baseband signal levels, bit-error rate (BER), modulation error rate (MER), frame error rate (FER).

   Intrinsic quality is directly relevant to the radio environment and to the proper system operation, and therefore strongly related to the broadcast standard, the engineering of the broadcast network, and the technology used within TV receivers and decoders.

   Note that intrinsic quality is a drastic condition for a system operation, but it has usually lower correlation with actual user's perception, especially on codecs that strive on the limitation of human perception to improve quality with reduced bandwidth, using non-linear and non-stationary transformations.

2) *Perceived quality by subjective methods*, where statistical instruments are used to evaluate user's perception on a media segment, based on the actual opinion of users, rated under controlled environment conditions and instruments. These procedures are technology independent, they can be seamlessly applied from narrow-band cheap radios to high-definition digital TV systems and will provide a reliable result if properly used, being, as such, the primary reference to which other quality evaluations are referenced, but with the major drawback of cost and time consuming.

3) *Perceived quality by objective methods*, where algorithms are created to combine several parametric quality indicators to provide a single quality grade that better correlates with a subjective evaluation.

All three procedures are usually based on the concept of inputting a test signal or pattern to the transmission/reception system and utilizing the output for analysis. The analysis itself can be made with or without the knowledge or measurement of the input signal.

Objective measurements of perceived quality usually require a comparison with the reference signal. Subjective methods may or may not use the reference, considering the alternatives when the evaluation is based on intelligibility and on the subjective perception of the listening test group. Intrinsic evaluation may be based on specific characteristics of the signal, such as cyclic redundancy codes (CRC), or r.m.s. power, and, as such, does not require the input signal to produce a result, or may need reference test patterns to provide specific results.

The perceived quality, especially when performing a subjective assessment, may also be divided into two classes: "quality assessment", when the target is to evaluate the system under optimum condition; and "impairment assessment", when the target is to evaluate the influence of coding, transmission or emission over the signal quality.

Subjective and objective quality evaluation procedures are described within ITU documentation. Considering audio in sound broadcasting, a starting point is Recommendation ITU-R BS.1283, that summarizes several other Recommendations on sound quality subjective assessment, which can be considered a reliable basis for quality evaluation. For high-quality systems, a basic reference for objective quality evaluation is Recommendation ITU-R BS.1387. The main reference for subjective perceived video quality evaluation is Recommendation ITU-R BT.500 which describes several methods that can be applied for the quality assessment.

Parametric evaluation was described when the standards in use were presented on the previous section.

A comprehensive performance analysis can be obtained by combining both intrinsic and perceived quality evaluations with traditional field strength and carrier to noise ratios for analogue standards, with additional radio propagation parameters such as signal to interference ratios, propagation delay spread, synchronisation delay spread for digital standards.

A common mistake on this subject is the misunderstanding that quality means users' satisfaction. In fact, it can be considered a scientific fact that the user's satisfaction is only proportional to the quality whenever this quality correlates with the expectations and desires of the consumer in a broader sense, i.e. one might not give importance to an excellent video quality, if the information presented is irrelevant.

Whenever a regulatory effort on quality is performed, the associated costs on monitoring should be considered and the final balance on the expected benefits to the user should be clear.

6.2.2 Broadcast standards and measurements

In this section the characteristics of the main standards in use worldwide for broadcast systems are presented. This description is focused on the spectrum occupancy features and main intrinsic quality parameters that can be used in each standard, being as such, focused on the spectrum monitoring applications.

6.2.2.1 Analogue AM sound broadcasting

AM sound broadcasting usually applies basic amplitude modulation with double sideband and carrier, allowing the use of very simple receivers, a key feature when these systems were implemented.

As described in Recommendation ITU-R BS.706, a data system similar to radio data system (RDS) implemented on the VHF band (Recommendation ITU-R BS.643) was also developed for the AM sound broadcasting services in the bands below 30 MHz. AM Data System (AMDS) was implemented in some countries, especially in Western Europe, using phase modulation over the main sound carrier and allowing transmission of data with up to 200 bit/s. The use of AMDS does not interfere with the standard spectrum occupancy characteristics of the AM sound broadcasting service.

6.2.2.2 Analogue FM sound broadcasting

A key reference for FM broadcast standards in use worldwide is Recommendation ITU-R BS.450. This Recommendation presents the standards for FM broadcasting in the VHF band, including radio frequency in use, pre-emphasis and general system characteristics for various countries.

FM stereo is composed mainly by a set of multiplexed carriers in the baseband signal, namely the mono audio (Left + Right channels), Pilot Tone, Stereo Audio (Left – Right), digital radio system (RDS, RBDS), SCA (subsidiary communication authority, auxiliary channel) and high speed and capacity data systems e.g. HSDS (High-Speed Digital System), DARC (Data Radio Channel), system "C2R[2]". The complete multiplex signal can consist of the mono signal from 0 to 15 kHz, the pilot tone at 19 kHz, stereo signal from 23 to 53 kHz, RDS at 57 kHz and for instance DARC from 76 to 86 kHz.

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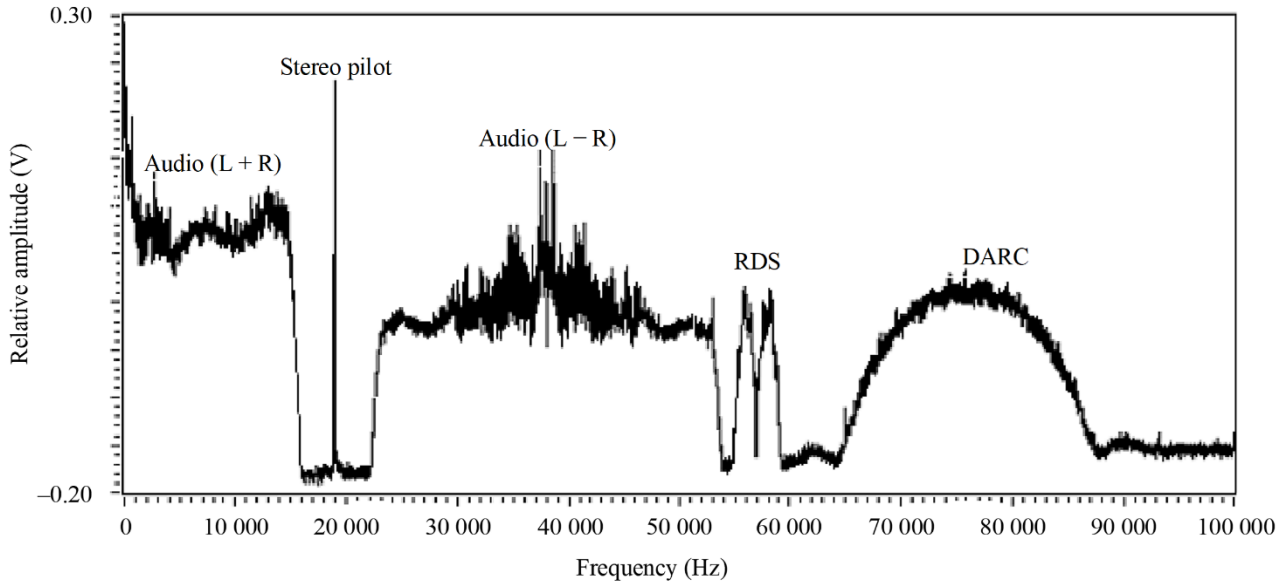
[2] TDF-C2R, *Centre d'Etudes en Radiodiffusion et Radiocommunication of Télédiffusion de France*, has developed in the 90s a dual-operating mode system for fixed and portable receivers which uses two different bit rates, multiplexed in time, called C2R.

FIGURE 6-49

Baseband spectrum of the FM multiplexed signal



Spectrum-5.2-01

Radio data system (RDS) was developed within the European Broadcasting Union in 1984, later adopted with enhancements by the EU in 1990, as the standard EN 50067 and by ITU in Recommendation ITU-R BS.643.

RDS uses an AM modulation with suppressed carrier by a shaped bi-phase data signal on a sub-carrier frequency of 57 kHz, locked in phase or in quadrature with the third harmonic of the pilot tone at 19 kHz. The result of this modulated signal is equivalent to a PSK transmission with data rates of about 1187.5 bit/s.

Radio broadcast data system (RBDS) was implemented in the United States of America based on the RDS but with modifications by NRSC (National Radio System Committee) in 1992. The modulation characteristics of RBDS are the same as the ones of RDS, and receivers designed for RDS will generally work with Radio Broadcast Data System (RBDS). The differences are mainly in the program type tables and other functionalities, not affecting the modulation and transmission layers.

Other data systems, intended for higher data rates (16 to 30 kbit/s) were also developed, one can mention the following: HSDS, DARC, "C2R", FMExtra. Information on HSDS and DARC can be found in Recommendation ITU-R BS.1194. These systems have limited success and will not be discussed in this chapter.

In order to minimize interferences between neighbouring FM sound broadcasting channels, Recommendation ITU-R BS.412 limits the maximum frequency deviation to ±75 kHz and the power of the multiplex signal (MPX) power, to the AF level of a sinusoidal tone with 19 kHz deviation.

This reference MPX power of 0 dB, averaged over a period of 60 seconds, must not be exceeded.

FM broadcasting service interference to aeronautical mobile systems used for navigation and surveillance purposes is a widely recognized problem.

Recommendation ITU-R M.1841 provides technical and operational requirements that may be used as a technical guideline for establishing the compatibility of the International Civil Aviation Organization (ICAO) ground-based augmentation system above 108 MHz and FM broadcasting systems operating up to 108 MHz.

Another critical problem connected to analogue FM sound broadcasting is the intermodulation created in aeronautical navigation receivers Instrument Landing System (ILS) and VHF omnidirectional range (VOR) due to multiple high-power signals on frequencies close to 108 MHz. Recommendation ITU-R SM.1009 describes the mechanisms and calculation procedures involved in all details.

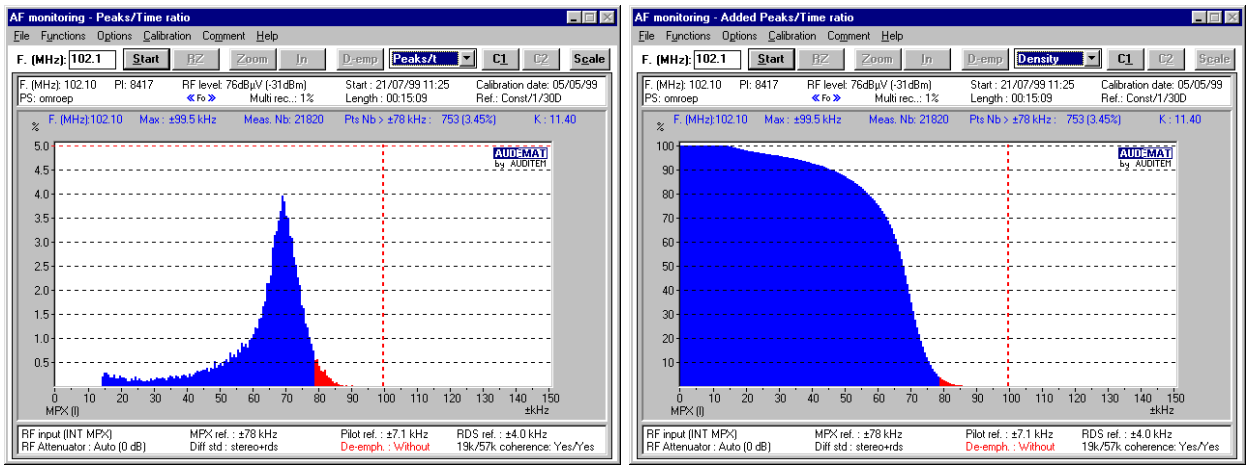
Because the spectrum of analogue sound broadcasting signals is much wider than the bandwidth of an ILS or VOR receiver, more than just one aeronautical radionavigation channel can be affected by this so-called "B1" interference. Apart from the input power to the receiver, how severe is this interference and the number of ILS or VOR channels affected depend on the maximum and average spectrum width of the FM sound broadcasting transmitters involved.

The maximum deviation determines the broadest RF spectrum and the MPX power determines the average spectrum. To avoid unnecessary interference, especially to the safety of life services such as VOR and ILS, both deviation and MPX power have to be measured by the monitoring service. In order to achieve accurate results, the equipment used for these measurements has to fulfil especial requirements that are described in Recommendation ITU-R SM.1268, together with detailed information about the measurement itself.

Recommendation ITU-R SM.1268 states that FM broadcasting emission should be observed over a period of 15 min. All the measured values, the peak values of the deviation in 50 ms, should be processed and a distribution plot and a complementary cumulative distribution function (CCDF) plot can be presented similar to those shown in the following figures. Note: the display of the statistical distribution curves depends on the measuring equipment used. It is necessary that this equipment should conform to Recommendation ITU-R SM.1268.

FIGURE 6-50

(a) Distribution plot and (b) complementary distribution function plot of the frequency deviation on FM broadcasting



a) b)

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Multipath propagation is a general problem for FM signals in the VHF bands and at higher frequencies. The result of multipath propagation in FM systems is unacceptable distortion of the modulated signal, such as that the indicated value on the FM modulation meter can be changed as much as by a factor of 2.

Due to multipath propagation, FM is converted into a certain percentage of AM by vectorial addition at the receive antenna. Therefore, multipath propagation can be found by measuring the AM of a frequency-modulated carrier. For this purpose, the modulation meter has to measure AM and PM/FM simultaneously.

For this purpose, instruments are in use, which offers parallel measurements of deviation and modulation depth with immediate calculation of the conversion factor, expressed in % modulation depth over kHz FM deviation.

Recommendation ITU-R SM.1268 defines maximum values for the amount of AM as well as other prerequisites for an accurate measurement.

6.2.2.3 Analogue TV broadcasting

Analogue TV broadcasting main standards defined are NTSC, PAL and SECAM.

Analogue test receivers can provide information on the vision carrier level, sound carrier level, deviation of the sound carriers, frequencies of vision and sound carriers, residual picture carrier, Incidental Phase Modulation (ICPM). Most of these measurements can also be performed by standard spectrum monitoring equipment that can usually provide basic information on the characteristics of the signal, mainly evaluating level, frequency and the differential relations of these parameters. Other information, such as incidental phase modulation, demands a system with vector analysis capabilities.

The spectrum characteristics, considering several variants of these main standards in use in different countries are presented in Recommendation ITU-R BT.1701 for bandwidths from 6 to 8 MHz.

6.2.2.4 Digital terrestrial sound broadcasting (DTSB)

Recommendation ITU-R BS.1114 presents six standards to be used in the VHF and UHF bands for digital terrestrial sound broadcasting. In this Recommendation these systems are referred to as Digital Systems A, F, C, G, H and I respectively, known commercially as Eureka 147 – DAB (Digital Audio Broadcasting), ISDB-T_{SB} (Integrated Services Digital Broadcasting – Terrestrial Sound Broadcasting), In Band On Channel Digital Sound Broadcasting (IBOC DSB), Digital Radio Mondiale (DRM), Convergent Digital Radio (CDR) and RAVIS (Realtime AudioVisual Information System). All systems operate with OFDM modulation in the channel coding, with the addition of convolution error correcting coding in the case of DAB. These are capable of providing "FM quality" reception with less than 200 kHz bandwidth per encoded audio programme, improving the spectrum efficiency. DRM operates under the name of DRM+ into the lower VHF band up to 120 MHz using channel bandwidths of 100 kHz.

Recommendation ITU-R BS.1615 presents two standards to be used in the HF, MF and LF bands, DRM and IBOC DSB. Both systems improve the quality of sound reception keeping the same bandwidth limits of the original analogue services that they are intended to replace.

The intrinsic quality evaluation for these systems usually is performed by measuring the BER and the SNR for systems A, F, H, I and G, and Block Error Ratio (BLER) and the *S*/*N* for system C. While the measurement of SNR is possible using standard monitoring equipment, the theoretical correlation of this ratio with the error rate might be extrapolated from laboratory studies, such as presented in Recommendation ITU-R BS.1114 for systems above 30 MHz and Recommendation ITU-R BS.1615 for systems below 30 MHz. The proper measurement of error rate should be performed using specialized equipment integrated in the respective decoder.

The measurement of the SNR is in fact troublesome, since the presence of the signal makes it impossible to evaluate the real noise level. One alternative is to temporarily turn off the emitter, an impossible task in most monitoring cases, except for experimental and initial trial purposes. Another alternative would be to extrapolate the noise level considering measurements performed on adjacent empty channels, far enough to avoid the spurious emissions from the carrier under evaluation but close enough to keep a reasonable correlation with the original channel noise value. Some automated measurement systems for digital systems are able to measure the Modulation Error Ratio MER.

MER is computed as the ratio between the power of an IQ signal and the power of the error vector, where this error is computed as the difference between the signal received and the expected IQ values, considering the ideal constellation as estimated by the receiver. MER measurements should be identical to the SNR when the only noise affecting the signal is a White Gaussian Noise, a situation not really found in the real world, where multipath and non-linear distortion effects are commonly seen.

In recent years studies on the intrinsic quality evaluation have been performed, and Report ITU-R BS.2502 explains measuring techniques that can be used in the evaluation of the digital audio broadcast (DAB) coverage. In this Report it is also described a method for the assessment of the quality of service based on the measured MSC BER before the Viterbi decoder.

Recommendations ITU-R BS.1114 and ITU-R BS.1615 detail the main characteristics for setup of monitoring equipment to perform evaluation of spectrum characteristics of the main digital terrestrial sound broadcasting standards.

The specific channel assignment depends on regional regulations in force.

When evaluating hybrid systems, which simultaneous broadcast (simulcast) analogue and digital signals such as proposed in HD radio and DRM, a simple objective measurement of quality can be achieved by recording the moments when the switching between analogue and digital demodulation takes place.

In these systems, the receiver switches automatically from analogue to digital as the error rate increases above a pre-defined threshold.

The use of such alternative should, although providing some benefits in terms of simplification of the system and procedures, must be carefully planned and used, since the obtained results might be restricted to the specific conditions of the receivers used, making it harder to compare these results with others that presents different performance characteristics.

In any case, it is highly recommended that the characteristics of the receiver, such as sensitivity and maximum acceptable error rate are well known.

6.2.2.5 Digital terrestrial TV broadcasting (DTTB)

Digital terrestrial TV broadcasting standards share the same band and channels used for analogue television. For this reason, the spectrum occupancy follows the same definitions as for the legacy systems. This concern has been stated in Recommendation ITU-R BT.798, and later explicitly defined in the form of protection masks in Recommendation ITU-R BT.1206. Due to this definition, all standards discussed are provided at least with alternatives for channel bandwidths of 6 MHz, 7 MHz or 8 MHz, in order to match the previously existing TV broadcast bandwidth in use.

The planning criteria for digital terrestrial television services are defined in Recommendation ITU-R BT.1368 (first generation systems, Advanced Television Systems Committee (ATSC), Digital Video Broadcasting-Terrestrial (DVB-T), ISDB-T, Digital Terrestrial Multimedia Broadcast (DTMB) and in Recommendation ITU-R BT.2033 (second generation systems, ATSC 3.0, DVB-T2, DTMB-A). Recommendation ITU-R BT.1306 and Recommendation ITU-R BT.1877 define error-correction, data framing, modulation and emission methods for, respectively, first and second generation systems.

Considering intrinsic quality parameters for digital television broadcasting standards due to the various topologies and engineering options of transmitter networks, and additionally, the numerous analogue to digital migration and frequency sharing scenarios among broadcasting networks, advanced intrinsic quality diagnostics might be essential to allow the proper application of spectrum monitoring resources, especially to solve interferences and promote the spectrum usage efficiency.

One special feature of some of the digital modulation standards is the possibility of creation of Single Frequency Networks (SFN), a condition where several transmitters are operating at the same frequency on the vicinity of each other, transmitting the same content. The basic objective of such network is to provide better coverage over an area using lower power transmitters, solving propagation limitations such as posed by terrain features and/or distance and thus providing better spectrum efficiency.

This possibility is created taking advantage of ability of digital transmission systems to provide multi-path cancelation and considering the multiple transmitters as a severe case of multi-path propagation. i.e. as long as the symbols transmitted are the same; the frequency is the same; and the time difference between transmitters are within acceptable limits, the receivers are able to decode the signal with no error.

The ability to operate on a SFN mode is inherent to any digital transmission scheme that provides fairly robust features against multi-path propagation and as such, can be easily used also for most OFDM transmission systems either for TV or sound broadcasting, although is more commonly applied to TV.

Especially when an SFN is in operation, but also in the case of Multi-Frequency Network (MFN), the use of specialized equipment able to perform detailed system analysis is required in order to properly evaluate the network performance, mainly because simple signal level measurements will not be able to determine if such network is operating within its modulation requirements and determine the cause of interference affected areas.

Recommendation ITU-R BT.1735 proposes methods to assist in the quality assessment of the reception of DVB-T services. Two procedures, based on the measured BER, one for MFN and one for SFN, are described.

Reports ITU-R BT.2467 and ITU-R BT.2495 introduce methods for evaluating the quality of service of second-generation digital television broadcasting systems (DVB-T2 the first and ATSC 3.0 the second) using the VHF and UHF bands. In particular, in Report ITU-R BT.2467, the proposed techniques consider the MER and the BER of the received signal.

An example of study of interference into the broadcasting service can be found in Report ITU-R BT.2265.

Report ITU-R BT.2389 details the measurement and monitoring principles for digital terrestrial television broadcasting.

6.2.2.6 Terrestrial multimedia broadcasting for mobile reception

Multimedia broadcasting technologies for handheld receivers in a mobile environment are being or have been developed. Recommendation ITU-R BT.2016 defines error-correction, data framing, modulation and emission methods of terrestrial multimedia broadcasting systems for mobile reception using handheld receivers in VHF/UHF bands.

6.2.3 Coverage measurements

General aspects and procedures for coverage measurements are described in § 5.11. This section describes specific methods suitable when measuring the coverage area of broadcasting networks.

Digital broadcasting systems can consist of single transmitters or whole networks covering a larger area, and they can be planned for different reception scenarios. The suitable coverage measurement method depends on various aspects such as:

– design of the network (single transmitter or single frequency networks (SFN);

– noise or interference-limited coverage;

– requirements of the licence (e.g. field strength only or QoS criteria);

– system aimed for fixed, portable indoor, portable outdoor or mobile reception;

– availability of planned/predicted coverage areas.

The most common measurement methods to assess the coverage of a broadcasting transmitter or network are

– field strength measurements at defined fixed locations or along a route;

– reception and QoS measurements with dedicated or commercial equipment.

In most cases coverage prediction maps will be available and the actual measurement is limited to verifying these predictions. Especially for large or even nationwide covered networks, actual measurements will mostly be limited to certain test areas or routes only and then extrapolated to the full coverage area or directly used to compare with predicted coverage.

For single transmitters and noise-limited coverage, a simplified method may be used where the relevant parameter (field strength or QoS) is measured at selected locations along radial routes that lead from the transmitter out beyond the coverage area.

Detailed descriptions of these measurement methods are contained in Recommendation ITU-R SM.1875 on the example of DVB-T/T2 transmitters and networks. However, these principles can also be applied to other digital broadcasting transmitters and networks.

6.2.4 Specific instruments used on broadcasting monitoring

As discussed on the introductory notes of § 6.2, in this sub-section are described general guidelines to expand the monitoring facilities by implementing additional monitoring channels adequate to radio signal monitoring and adequate to content monitoring.

Information recorded by the additional channels can be used to help identifying transmitters, ascertain compliance with specific content regulations, such as commercial use of non-commercial licensed channels, and even evaluation of transmission characteristics, such as operating time and spectrum occupancy, night time power reduction for HF broadcasting or objective image and sound quality parameters.

According to national needs, a network of such stations can provide auditing capabilities to several different organizations evaluating different obligations of broadcasting service providers, including taxation over media production, copyright protection or even civil rights.

Much like for standard spectrum monitoring facilities, the regulator can implement content monitoring stations of different types. Most of the time, considering the small size of such stations, it might be of interest to implement this content monitoring channel as an additional resource of standard spectrum monitoring stations. For example, once a transmission is detected, a secondary recorder is activated, freeing the monitoring receiver to proceed with the scan over a wider frequency span.

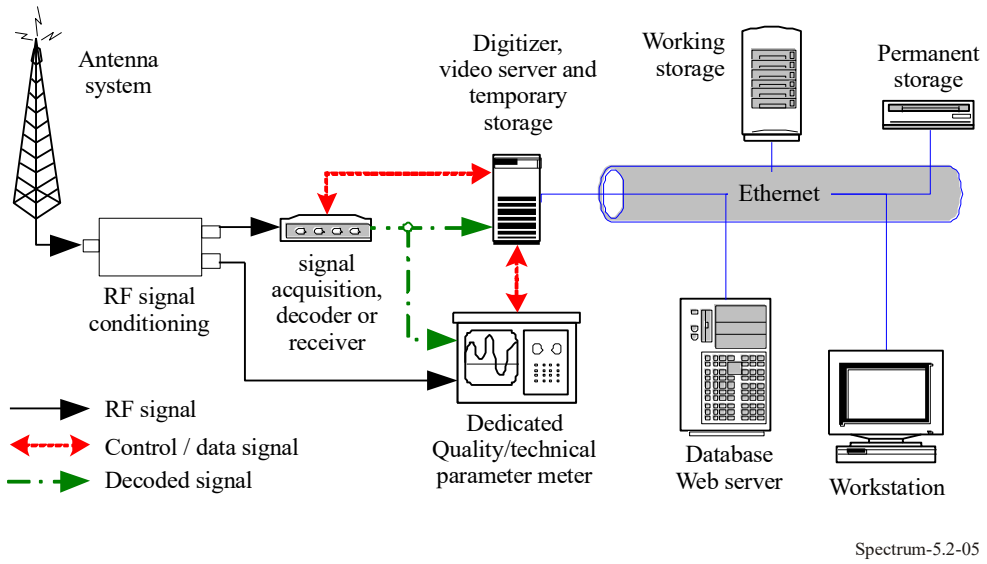
6.2.4.1 General topology

Modern monitoring systems can largely benefit from the state-of-art software design practices, including the use of scalable and reusable software components, such as API, Browser components and commercial communication standards such as TCP/IP, HTML and Web services to provide a more flexible and easy to integrate platform.

The following diagram presents a simplified platform architecture for content monitoring. From this diagram, the following sections are defined, providing more detailed information on each element.

FIGURE 6-51

Simplified platform architecture for content monitoring



Such platform can be implemented either as a fixed station, or integrated on mobile or transportable stations. Several of the above functions might be integrated into a single device.

6.2.4.2 Antenna system

The number, size and type of antennas should be chosen in such way to accommodate specific signal characteristics and installation conditions.

For fixed FM sound broadcast receiving installations, Recommendation ITU-R BS.599 suggests the use of directive antennas. These kinds of antennas will significantly reduce the probability of interference and increase the sensitivity. The directivity mask of antennas, in the two considered receiving scenario (Mono and Stereo) presented in this Recommendation, either in vertical and horizontal polarizations, is presented in Fig. 6-52.

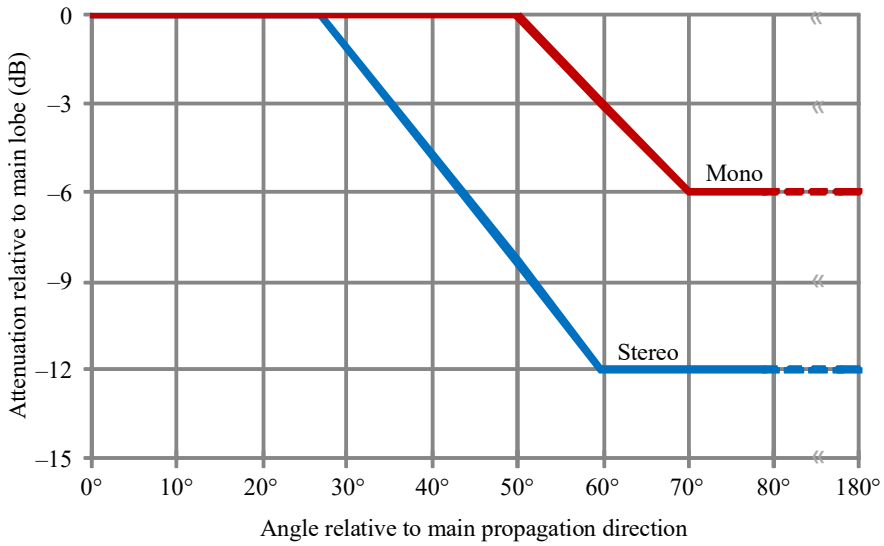
The use of directive antennas is also recommended in order to reduce the influence of undesirable propagation effects.

In case of mobile monitoring stations, preference should be given to non-directional antennas or antenna arrays, at least on the horizontal plane. This usually is performed by monopoles (ground plane antennas) or arrays of antennas. Monopoles, dipoles and discone antennas might be good alternatives as passive antennas for the VHF bands.

For more specialized mobile systems, aimed for example to perform interference analysis on SFN networks, or to be used on network optimization tasks, the use of antenna arrays and of adaptive spatial processing with interference mitigation capabilities is desirable since it may provide better flexibility and performance in terms of signal-interferer rejection, including in cases of correlated signals over the same frequency, such as observed over SFN.

FIGURE 6-52

Directivity of receiving antenna for fixed monitoring site in case of Mono or Stereo reception



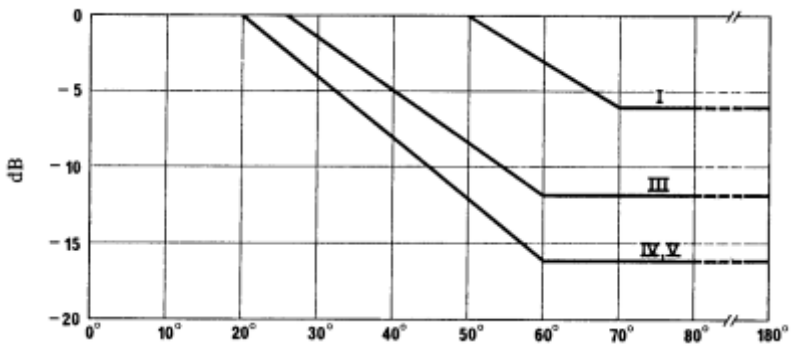
Spectrum-5.2-06

For fixed television receiving installations, Recommendation ITU-R BT.419 proposes the following values for antenna gain:

FIGURE 6-53

Discrimination obtained by the use of directional receiving antennas in broadcasting

(The number of the broadcasting band is shown on the curve)



As stated in the referred Recommendations, these values are generally used as reference for planning and, as such, might be used to implement a reference station that is in accordance with the general user.

For digital television systems, Recommendation ITU-R BT.1368 proposes typical values for antenna discrimination in case of different receiving scenario (Fixed, Portable and hand-held reception).

RF conditioning:

The RF conditioning devices include switching, distribution, cabling, low noise amplifiers and filters to promote optimum receiving quality while maintaining realistic user's conditions.

As a reference, the sensitivity levels discussed below should be considered when designing such a subsystem.

6.2.4.3 Reception and decoding

In the simplest cases the signal reception and decoding are usually performed by standard commercial video and audio receivers/tuners and decoders.

When more detailed analysis is required, the signal reception and decoding may include adaptive spatial filters in order upgrade the demodulation and the decoding performances.

Ideally the system should be flexible enough to be easily integrated with standard commercial receivers/decoders, enabling the easy monitoring of digital broadcasting on different standards, and coded pay-TV services operating over cable, satellite or terrestrial.

The signal acquisition, considering receivers, RF conditioning and antenna systems, should provide sensitivity in accordance with minimum field strength as per the following Recommendations:

- ITU-R BS.703 for the analogue AM sound broadcasting;
- ITU-R BS.704 for FM sound broadcasting;
- ITU-R BS.1615 for digital sound broadcasting below 30 MHz;
- ITU-R BS.1660 for digital sound broadcasting in the VHF band;
- ITU-R BT.804 for analogue TV broadcasting;
- ITU-R BT.1368 and ITU-R BT.2033 for digital TV broadcasting.

The implementation of the additional content monitoring channel may also be done by the integration of radio scanners, such as the ones used by amateur radio. Compared to commercial broadcast receivers, such scanners might lack the proper decoding capabilities but might provide benefits such as larger operational frequency range and automation resources, enabling the provision of a transparent user interface for a mixed monitoring system, composed by the standard measuring channels, such as described on Chapter 3, and additional content monitoring channels.

6.2.4.4 Dedicated quality/technical parameter meter

On most cases, basic service evaluation such as coverage and spectrum mask can be performed by standard monitoring equipment combined with standard commercial video and audio receivers/tuners and decoders. For digital broadcasting, receivers that perform some basic intrinsic quality measurements, such as BER, are commonly used but to fully evaluate the characteristics of broadcasting networks, specialized equipment are needed, especially to solve complex interference cases, such as may be observed on SFN.

Experimental studies, such as Project IST-2000-26222 ANTIUM "DVB-T multi-channel processing report", indicate that such system, including receiver, decoder and antennas, should provide from 10 to 20 dB of interference rejection capability more than regular terminals, so that reliable interference diagnosis and signal measurements can be achieved, including proper decoding of the signalling channel, allowing the identification of essential parameters such as guard time modulation and coding schemes.

6.2.5 References

NOTE – In every case the latest edition of the ITU-R Recommendations and ITU-R Reports should be used.

6.2.5.1 ITU-R Recommendations

Recommendation ITU-R BS.412 – *Planning standards for terrestrial FM sound broadcasting at VHF*

Recommendation ITU-R BS.599 – *Directivity of antennas for the reception of sound broadcasting in band 8 (VHF)*

Recommendation ITU-R BS.643 – *System for automatic tuning and other applications in FM radio receivers for use with the pilot-tone system*

Recommendation ITU-R BS.703 – *Characteristics of AM sound broadcasting reference receivers for planning purposes*

Recommendation ITU-R BS.704 – *Characteristics of FM sound broadcasting reference receivers for planning purposes*

Recommendation ITU-R BS.706 – *Data system in monophonic AM sound broadcasting (AMDS)*

Recommendation ITU-R BS.1114 – *Systems for terrestrial digital sound broadcasting to vehicular, portable and fixed receivers in the frequency range 30-3 000 MHz*

Recommendation ITU-R BS.1194 – *System for multiplexing frequency modulation (FM) sound broadcasts with a sub-carrier data channel having a relatively large transmission capacity for stationary and mobile reception*

Recommendation ITU-R BS.1283 – *A guide to ITU-R Recommendations for subjective assessment of sound quality*

Recommendation ITU-R BS.1387 – *Method for objective measurements of perceived audio quality*

Recommendation ITU-R BS.1615 – *Planning parameters for digital sound broadcasting at frequencies below 30 MHz*

Recommendation ITU-R BS.1660 – *Technical basis for planning of terrestrial digital sound broadcasting in the VHF band*

Recommendation ITU-R BT.419 – *Directivity and polarization discrimination of antennas in the reception of television broadcasting*

Recommendation ITU-R BT.500 – *Methodology for the subjective assessment of the quality of television pictures*

Recommendation ITU-R BT.798 – *Digital television terrestrial broadcasting in the VHF/UHF bands*

Recommendation ITU-R BT.804 – *Characteristics of TV receivers essential for frequency planning with PAL/SECAM/NTSC television systems*

Recommendation ITU-R BT.1206 – *Spectrum shaping limits for digital terrestrial television broadcasting*

Recommendation ITU-R BT.1306 – *Error correction, data framing, modulation and emission methods for digital terrestrial television broadcasting*

Recommendation ITU-R BT.1368 – *Planning criteria for digital terrestrial television services in the VHF/UHF bands*

Recommendation ITU-R BT.1701 – *Characteristics of radiated signals of conventional analogue television systems*

Recommendation ITU-R BT.1735 – *Methods for objective reception quality assessment of digital terrestrial television broadcasting signals of System B specified in Recommendation ITU-R BT.1306*

Recommendation ITU-R BT.1877 – *Error-correction, data framing, modulation and emission methods and selection guidance for second generation of digital terrestrial television broadcasting systems*

Recommendation ITU-R BT.2016 – *Error-correction, data framing, modulation and emission methods for terrestrial multimedia broadcasting for mobile reception using handheld receivers in VHF/UHF bands*

Recommendation ITU-R BT.2033 – *Planning criteria, including protection ratios, for second generation of digital terrestrial television broadcasting systems in the VHF/UHF bands*

Recommendation ITU-R M.1841 – *Compatibility between FM sound-broadcasting systems in the frequency band of about 87-108 MHz and the aeronautical ground-based augmentation system in the frequency band 108-117.975 MHz*

Recommendation ITU-R SM.1009 – *Compatibility between the sound-broadcasting service in the band of about 87-108 MHz and the aeronautical services in the band 108-137 MHz*

Recommendation ITU-R SM.1268 – *Method of measuring the maximum frequency deviation of FM broadcast emissions at monitoring stations*

Recommendation ITU-R SM.1875 – *DVB-T/T2 coverage measurements and verification of planning criteria*

NOTE – In every case the latest edition of the Recommendation should be used.

6.2.5.2 ITU-R Reports

Report ITU-R BS.2502 – *Measuring techniques for digital audio broadcast coverage performance*

Report ITU-R BT.2265 – *Guidelines for the assessment of interference into the broadcasting service*

Report ITU-R BT.2389 – *Guidelines on measurements for digital terrestrial television broadcasting systems*

Report ITU-R BT.2467 – *Methods for the evaluation of the quality of service of second generation DTTB system*

Report ITU-R BT.2495 – *Methods for laboratory and field measurements for the assessment of ATSC 3.0 reception quality*

NOTE – In every case the latest edition of the Report should be used.

6.2.6 Other references

LOUBATON, P.; MASSE, D.; MHIRI, R.; SCHAFHUBER, D. [2003] *DVB-T multi-channel processing report*; Project IST-2000-26222 ANTIUM: deliverable D3031b; Version 1.0

6.2.7 Abbreviations/Glossary

AMDS	AM data system
BER	Bit error rate
BLER	BLock error rate
CCDF	Complementary cumulative distribution function
CRC	Cyclic redundancy checksum
DARC	Data radio channel
DRM	Digital Radio Mondiale
DTSB	Digital terrestrial sound broadcasting
DTTB	Digital terrestrial TV broadcasting
FER	Frame error rate
HSDS	High speed data system
ICPM	Incidental phase modulation
ILS	Instrument landing system
IQ	In-phase and quadrature components
MER	Modulation error ratio
MFN	Multi-frequency networks
MPX	MultiPlex signal
MSC BER	Main service channel bit error rate

OFDM	Orthogonal frequency division multiplexing
QoS	Quality of service
RBDS	Radio broadcast data system
RDS	Radio data system
SCA	Subsidiary Communication Authority
SFN	Single frequency networks
SIR	Signal to interference ratio
SINR	Signal to interference plus noise ratio
SNR	Signal to noise ratio
THD	Total harmonic distortion
VOR	VHF omnidirectional range

6.3 Monitoring of cellular systems

6.3.1 Introduction

In the context of this section, the term "cellular systems" is used to comprise all mobile radio systems providing direct or indirect access to public telecommunication networks such as public telephone networks or the Internet. Personal communication systems (PCS) such as DECT are not covered in this section for the following reasons:

– they operate in licence-exempt bands requiring little or no monitoring activity;

– measuring their emissions does not require specific procedures, equipment or settings.

Mobile satellite services are covered in § 6.4 because they are a specific case of satellite uplinks.

Cellular radio systems are different from other land mobile radio systems in several ways. They offer:

– increased call capacity to accommodate larger numbers of users;

– improved quality of service over larger geographic areas;

– better utilization of radio frequency spectrum.

Nowadays the same cellular systems/services/networks are commonly used for mobile as well as stationary access to the Internet with a wide range of user equipment such as smartphones, tablets and routers. Therefore, this section does not distinguish between what is often called "mobile radio service" and "broadband wireless access".

Cellular radio systems utilizing analogue standards have been in operation in the past around many parts of the world. However, such systems are almost universally replaced or upgraded to digital cellular radio systems. Analogue standards were known as the first generation of cellular radio systems. Monitoring of these systems is not covered in detail in this section.

Digital cellular systems have been introduced as the second generation (2G) networks. Apart from the European GSM standard, several other 2G standards such as TIA/EIA-136 in North America, and ARIB RCR STD-27 (known as PDC) in Japan.

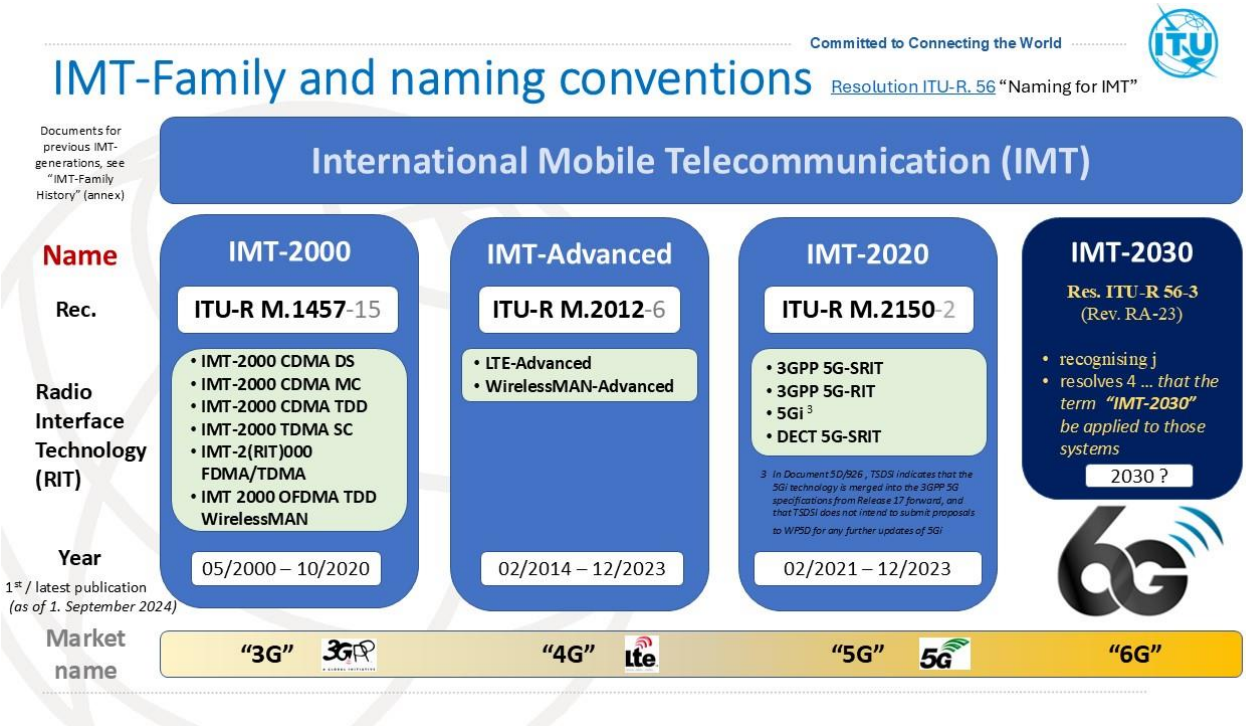
The third generation of cellular systems (3G) uses CDMA as the access technology. Apart from the European Universal Mobile Telecommunications System (UMTS), several other 3G standards were in use such as TIA/EIA-95 (known as IS-95) in North America, ARIB T-53 in Japan Telecommunications Technology Association (TTA).KO-06 0003 Korea.

Recently, almost all countries in the world have been moving to standards defined by the 3rd Generation Partnership Project (3GPP). This allows customers to use their mobile devices in almost all countries. From 2G/GSM through 3G/UMTS and 4G/LTE, 3GPP specifications have reached the 5th generation 5G/NR, and development of further generations is ongoing.

Figure 6-54, presentation of Counsellor ITU-R SG5, EU/CNC 6G Summit 9 June 2023, depicts the IMT-Family and naming conventions.

FIGURE 6-54

IMT-Family and naming conventions – Resolution ITU-R 56[3] "Naming for IMT"



Due to their wide spread throughout the world, this section will concentrate on 3GPP systems. The sections on each technology or generation of cellular systems contain a description of the physical layer (or radio layer) as basic knowledge of the function is necessary to understand the described methods to measure Radio Frequency (RF) parameters and investigate cases of interference to these networks.

6.3.2 General description of the IMT systems and common monitoring procedures

The ITU Radio Regulations specify the updated RF bands identified for IMT, and the related footnotes. Although an increasing number of frequency bands are allocated to the public mobile service, a major limitation of any cellular radio system is the availability of radio frequency spectrum. All cellular radio systems utilize frequency (channel) re-use and enable controlled handovers between defined geographical areas known as cells. The size of a cell is determined by the geographical coverage area of a given signal strength from a base station transmitter operating within that cell.

Figure 6-55 shows the simplified architecture of a digital cellular radio system using the example of GSM. To minimize the number of base stations, they are usually placed at the intersection of three hexagonal shaped cells that are served individually by directional sector antennas with an opening angle of 120 degrees.

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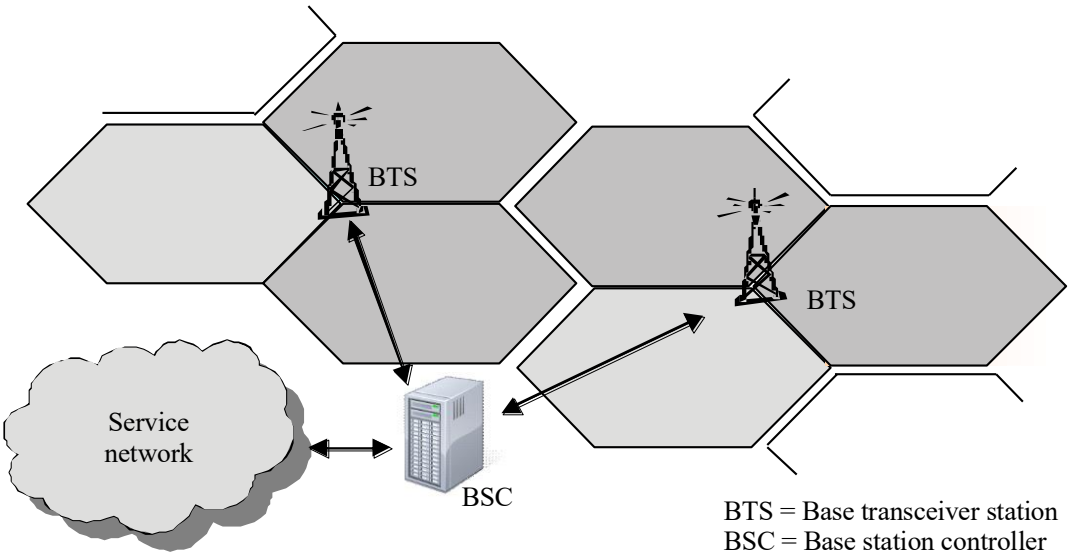
3 While care is taken to refer to the official definition of IMT-generations, parts of this document contain material, which refers to the frequently used market names "xG". In general, IMT-2000, IMT-Advanced, IMT-2020 and IMT-2030 are known as 3G, 4G, 5G and 6G, respectively.

FIGURE 6-55

GSM network architecture



Spectrum-5.3-01

A so-called handover process automatically switches control of the mobile terminal (handset, or other user equipment) and connection to the adjacent cell when it moves into a new geographic area covered by a different base station transceiver (BTS) usually operating with one or more of the following techniques:

– on a different RF channel for frequency-division multiple access (FDMA);

– on a different time slot for time-division multiple access (TDMA);

– with different orthogonal spreading codes on the same RF channel for code-division multiple access (CDMA);

– using different parts of the spectrum for a limited time (OFDMA).

In some networks, it is possible to serve a mobile unit from more than one base station simultaneously. So-called “soft handovers” seamlessly spread the user data stream over two or three base stations depending on their receiving situation at the location of the mobile.

User data is grouped in time frames which are transmitted sequentially. For a more detailed description of the above-mentioned multiplex methods, see § 7.6.

The main tasks for Monitoring Services on cellular systems are:

– On-site inspections to verify compliance with licence conditions.

– Interference investigation.

– Coverage measurements.

While coverage measurements often follow a technology-independent procedure, they are covered for all technologies in a combined § 5.11. Methods specific to cellular networks are described in §§ 6.3.4 to 6.3.7. Measurement of basic RF parameters and interference investigation, however, strongly depends on the cellular technology, both regarding necessary equipment and procedures. They are therefore covered under each technology separately.

For simplicity, in this section, we refer to the base transmitter units as “Base Station” (BS) and for the mobile terminal (e.g. handset, smartphone, router, computer) as “User Equipment” (UE).

For most common monitoring tasks ("measurement of RF signals" in the following sections such as identification of technology, frequency and bandwidth), however, it is sufficient to identify the network or BS that is currently measured. In cellular radio networks, each BS has a unique identification number that is continuously transmitted via broadcast or organizational channels without encryption. To read this always-on information, the monitoring system such as a passive network scanner must be able to synchronize and decode the data stream, but it is not necessary to actively participate in the service or log on to the network.

Before an uplink interference report is investigated, it is necessary to ensure that the mobile network operator has thoroughly checked and ruled out uplink interference caused by internal network issues or hardware faults.

The basic approach to investigate reported uplink interference, independent of the technology, is as follows:

1) Coordinate with mobile network operators to collect as much relevant interference data as possible, including data on the affected BS and its neighbouring BSs, preferably also from other operators sharing the same site. All mobile base stations perform internal measurements of the interference level. The information available from these measurements depend on the cellular system and is described in the relevant section below. These data help to identify the beginning, occurrence time, and duration of the harmful interference, the interfered frequency range, and the area suspected of containing the interfering source. It is necessary to collect interference data for several days prior to receiving the interference report, maintain data collection throughout the interference-handling process, and continue afterward to accurately assess the interference source. On a national basis it may even be possible to develop procedures/tools to allow direct connection with mobile network operators to collect real-time or near real-time interference data from the above-mentioned base stations, thereby maximizing the efficiency for the interference-handling team.

2) Start at the bottom of the affected base station, in the direction of the most affected sector. Preferably use a mobile monitoring station with a highly directional antenna and turn it through the angle range of the affected sector. Prerequisites such as shutting down the affected station, required equipment and settings depend on the cellular technology and is described in the relevant section below.

3) If no interference is visible, connect the measurement equipment directly to the affected sector antenna of the base station. Here, the interfering signal must be visible and with suitable settings of the measurement equipment (e.g. RBW of a spectrum analyser is equal to the bandwidth in which the base station measures) the measured interference level should be in the order of what is reported from the base station.

4) Record the RF properties of the interfering signal: exact frequency and behaviour of narrowband interferers, bandwidth and specific properties of broadband interferers, pulse length and repetition rate of pulsed interferers. This information helps to find optimal settings for the measurement equipment in the following steps.

5) Try to receive the interfering signal with portable monitoring equipment and a directive handheld antenna positioned as close to the base station as possible (e.g. perform a measurement on the roof or outside top story windows in case the base station is roof-mounted, climb the mast in case it is a mast installation).

6) Once the interfering signal is received with the portable equipment, determine the bearing of the interferer from the location of the base station.

7) Using mobile or portable equipment, follow the bearing until the interferer is located. If possible, switch off the interferer and ask the operator of the base station if the interference is gone.

Especially the high gains of base station antennas make them extremely sensitive. Experience shows that standard monitoring receivers and analysers are often not sensitive enough to receive interfering signals. It is therefore recommended to use (external) low-noise preamplifiers when searching for interference. However, they can only be used in combination with a band pass filter tuned to the uplink band because otherwise the measurement equipment will be overloaded by the strong downlink signals.

6.3.3 Common interference sources

This section describes two common interference sources that may affect all cellular systems.

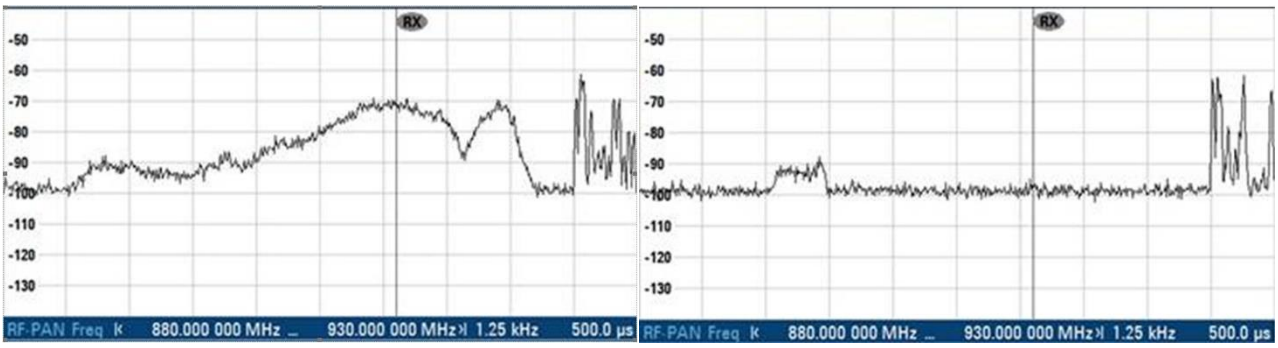
6.3.3.1 Unauthorized cellular repeaters

While frequency-selective repeaters may even be installed by the network operators, the cheaper broadband repeaters covering all cellular bands and all operators are generally illegal and are a widespread source of interference. They produce a broadband noise-like signal over the whole uplink band and weakening over a few MHz beyond the band edges. Due to frequency-selective fading and other effects, the noise level may not be constant over the whole band, but include peaks and notches. Their noise signal can usually only be received with monitoring equipment in a range of not more than about 500 m. In addition, repeaters may also emit other signals like unmodulated carriers as they pick up and re-transmit any RF signal from electrical/electronic devices that is present at the indoor site of the repeater.

Figure 6-56 shows a spectrum of a repeater in the 900 MHz uplink range. The left side of the Figure shows the spectrum when the repeater is on, the right side when it is switched off.

FIGURE 6-56

Example spectrum of a repeater (left: repeater on; right: repeater off)

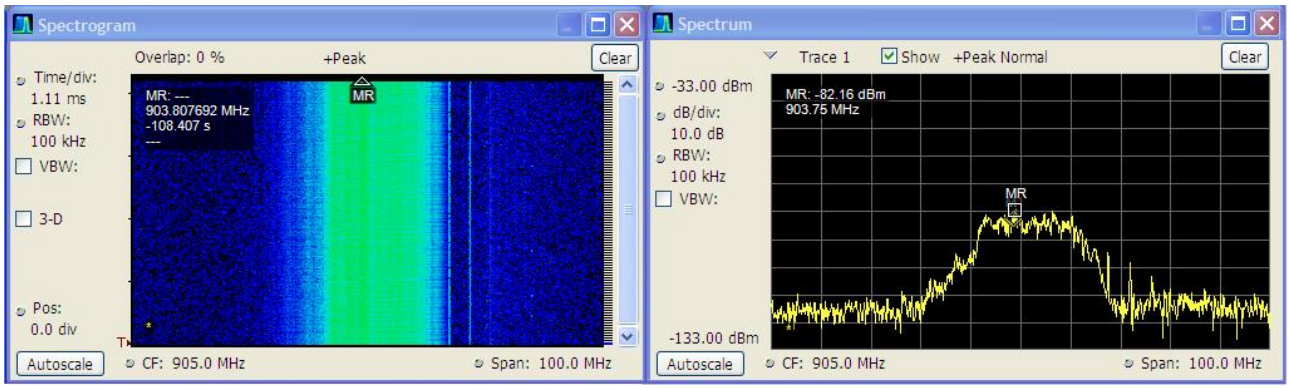


6.3.3.2 Jammers

Jammers produce a broadband spectrum over the whole uplink and/or downlink bands. Most common are fast sweeping carriers producing a near rectangular spectrum, or noise-like modulations producing a spectrum like a digital signal. Usually they transmit not only in the affected band, but also in other frequency bands allocated to the cellular service. Figure 6-57 shows an example of a jammer producing a noise-like signal in the 900 MHz downlink band, recorded in front of the building in which it was installed.

FIGURE 6-57

Example spectrogram and spectrum of a jammer



Especially when installed indoors, measurements recorded outdoors may not show the original spectrum because of frequency-selective building attenuation and reflections.

Section 6.3.2 provides other elements on common monitoring procedures.

6.3.4 2G/GSM

6.3.4.1 System description

The second generation of cellular systems was designed mainly for the transmission of speech. As this service does not require high data rates, the signals are relatively narrow in bandwidth. The increasing demand to also transmit user data led to enhancements of the GSM system such as "General Packet Radio Service" (GPRS) and "Enhanced Data rate for Global Evolution" (EDGE). While the standard gross data rate is 270 kbit/s, these enhancements made data rates up to 59.2 kbit/s on one RF channel possible.

The Global System for Mobile Communications (GSM) is usually operating in the 900 MHz and 1 800 MHz bands (1 900 MHz in North America).

Table 6-13 lists the relevant RF parameters of the GSM system.

TABLE 6-13

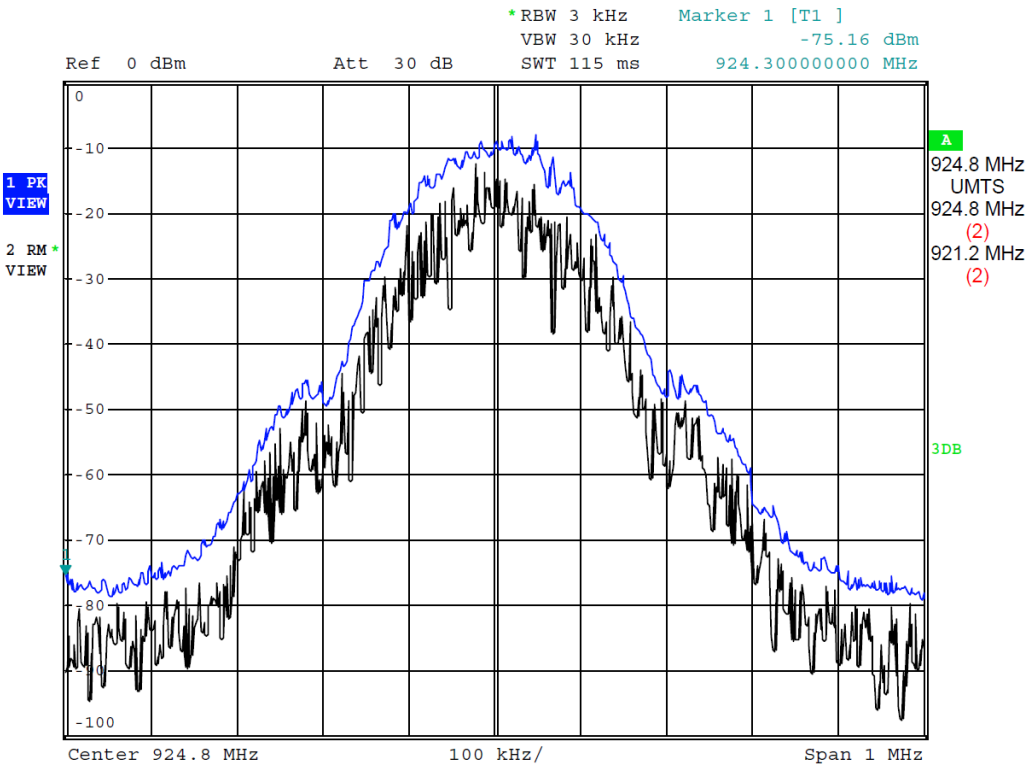
Relevant air interface characteristics of GSM

Parameter	Value(s)
Modulation	GMSK (EDGE: 8-PSK)
Symbol rate (ksymb/s)	270.833
Occupied bandwidth (kHz)	250
Channel spacing (kHz)	200
Multiple access	Combined FDMA and TDMA
Duplex method	FDD
Duplex spacing	45 MHz (GSM900) 95 MHz (GSM1800, GSM1900)
Frame length (ms)	4.62
Timing	8 time slots at 576.6 µs

Figure 6-58 shows the Peak and RMS spectrum of a GSM signal.

FIGURE 6-58

GSM spectrum

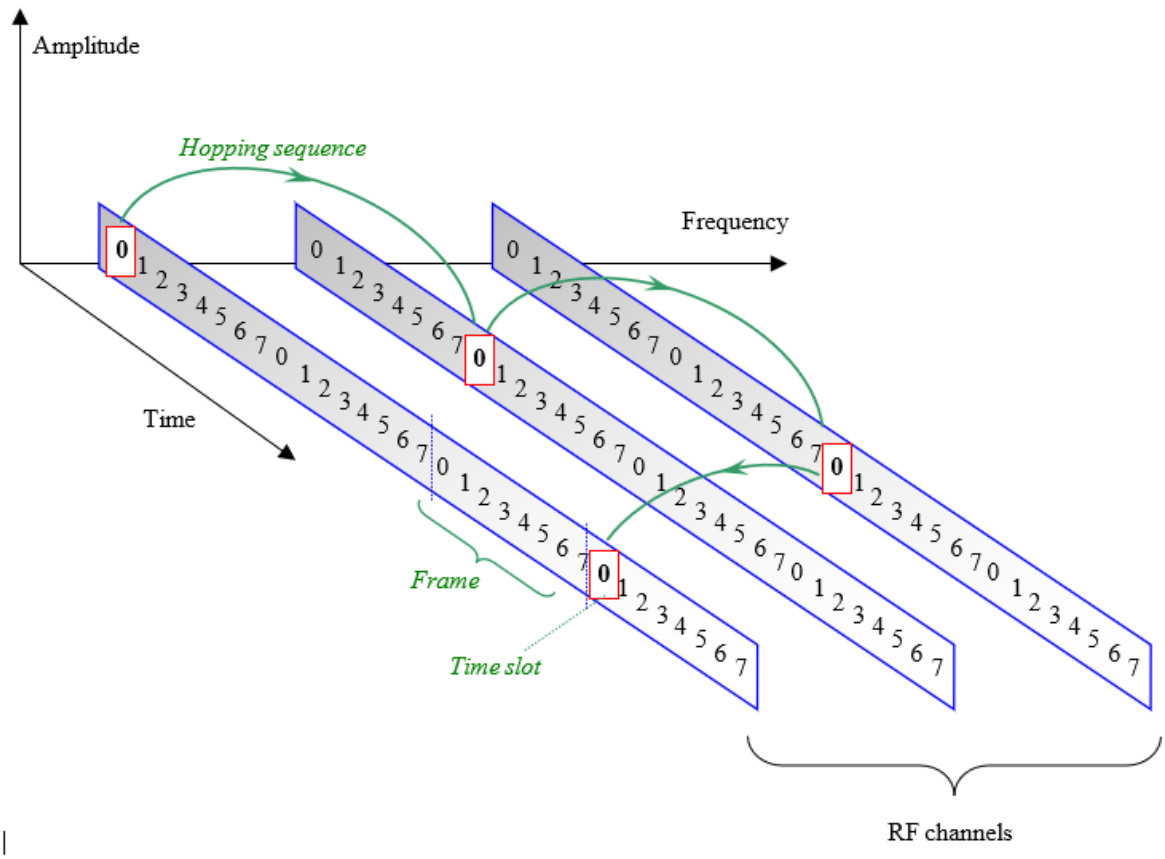


A GSM BS uses at least one RF frequency, called C0. One of the 8 time slots on this frequency is used to transmit the broadcast information. This time slot is called Broadcast Control Channel (BCCH). It is the only traffic-independent signal and always transmitted with full power. The remaining time slots of the C0 are usually also transmitted with full power. They can be used for user traffic, or filled with dummy data. Time slots with user traffic may also be transmitted with reduced power if the user equipment (UE) reports good receiving conditions.

Most GSM BS use multiple RF channels. This allows combining FDMA and TDMA when serving their UEs. The frequency of a connection is changed after each radio frame (every 4.62 ms), resulting in a frequency hopping signal. This increases resistance against frequency-selective interferers.

FIGURE 6-59

Example of TDMA and FDMA combination in GSM



One effect of this architecture is that only the frequency carrying the BCCH is constantly on air. Additional channels are only transmitted if user traffic is present.

6.3.4.2 Measurement of RF parameters

Identification of technology

Identification of a GSM signal and separation from other cellular technologies is simple and can be done by displaying the MaxHold spectrum of a channel with a spectrum analyser. The result, however, may not show one single channel as in Fig. 6-58, because the channel spacing of 200 kHz and a bandwidth of 250 kHz results in overlapping spectra. On the other side, also due to the overlap, a base station cannot use adjacent channels. This means that if using a directional antenna pointed to the nearest base station, their channels must have higher received levels than all others. This makes it also possible to identify the traffic channels used by the BS in question by selecting a long MaxHold time.

Frequency and bandwidth

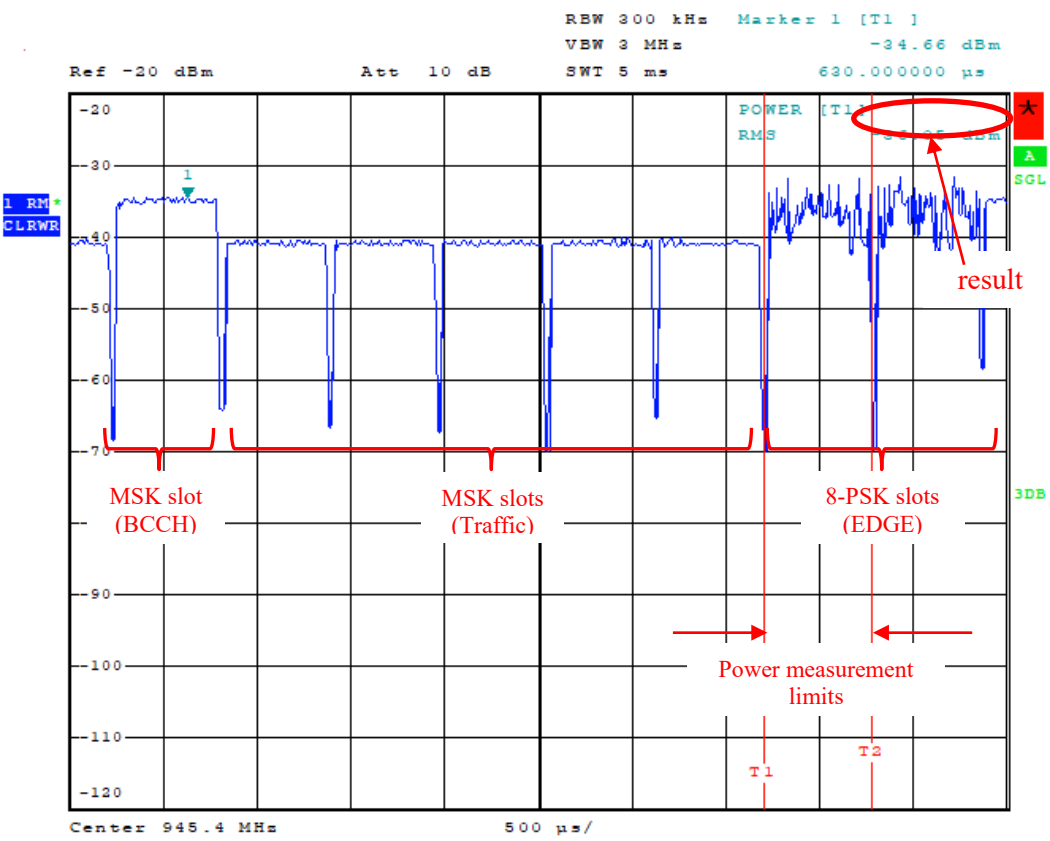
As mentioned above, GSM base stations often use more than one frequency or RF channel. Additional frequencies, however, may appear only if user traffic is present. The C0 frequency is always transmitted, and with full power. So, in most cases this is the most interesting frequency to perform all measurements on. The channel spacing is 200 kHz, and the centre frequencies are always on even 100 kHz (e.g. 910.6 MHz, 910.8 MHz, but not 910.65 MHz or 910.7 MHz). The bandwidth can be measured using the occupied bandwidth measurement function on the MaxHold recording, or by placing markers about 15 dB below the top level.

Level

Because the GMSK modulation does not have an amplitude component, the received level of a GSM time slot is normally constant. This would normally allow a correct level measurement of a GSM signal by using the peak detector and a measurement time of at least 4.62 ms. If there are EDGE slots, however, the 8-PSK modulation causes a peak/average ratio of about 3 dB. This has to be considered when measuring the level of a GSM signal. In this case, a time domain measurement has to be performed, limiting the level measurement to the BCCH slot only, or, if the measurement device permits, calculating the average level from a selected EDGE slot, as in Fig. 6-60.

FIGURE 6-60

Time domain level measurement in GSM



Section 6.3.2 provides other elements on common monitoring procedures.

6.3.4.3 Interference investigation

Information from the base station

Like all 3GPP technologies, GSM base stations perform internal measurements of the interference level. This information should be requested from the operator reporting interference. In GSM, measurement of the remaining input level on unused time slots in the corresponding uplink band takes place. This is called "Idle Channel Measurement" (ICM). However, this measurement may be performed not only on the C0 uplink frequency, but also on any of the traffic channels.

Evaluation of the interference is done by grouping the level into so-called "interference bands" (IB). These bands are not to be mixed with frequency bands. The interference bands range from 0 for "no interference" up to 5 for "extreme severe interference". Table 6-14 shows the corresponding received levels of interference for these bands.

TABLE 6-14

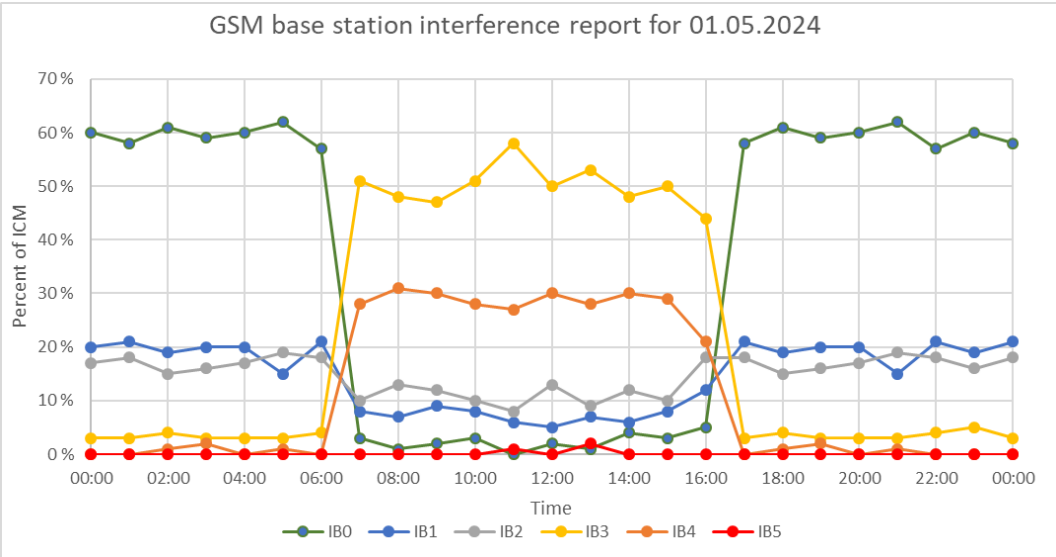
GSM ICM interference bands and interference levels

Interference band	Interference level (dBm)
0	< −110
1	−110 to −108
2	−108 to −104
3	−104 to −98
4	−98 to −88
5	> −88

The BS reports a statistical evaluation of measurements in each interference band over a given observation time, typically 15 minutes. Visualization of the interference reports varies and depends on software, vendor of the BS and operator settings. Figure 6-61 shows one possible example.

FIGURE 6-61

GSM base station uplink interference report (example)



The example in Fig. 6-61 shows an interferer that was present only during working hours between 07:00 and 16:00. In this time, most of the results of the ICM were in band 3 and 4, corresponding to an estimated interference level of about −100 dBm. At night, the results were between IB 1 and 2, corresponding to an interference level around −108 dBm, which may be the normal noise environment at that location.

This information from the operator provides valuable information for interference hunting. For intermittent interferers, the times of presence can be seen, and the received level of the interfering signal at the base station antenna can be estimated.

Recommended procedure

Since GSM operates in frequency division duplex (FDD), the interferer must be in the uplink band. When following the general procedure described in § 6.3.2 above, the following specialties for GSM apply:

1) Shut down the affected base station. This is necessary to receive the interfering signal without being masked by signals from served UEs.

2) If no narrowband signal is receivable, compare the noise level inside the GSM uplink band with that outside this band.

3) The received level of the interferer when measured at the affected base station antenna should be in the order of the level from the ICM, when measured in the time domain as in Fig. 6-61. To achieve similar levels with a spectrum analyser as reported by the base station, it is important that the RBW is at least 200 kHz.

Common interferers

1) Amplifiers from active TV antennas. They usually produce a narrowband carrier that is instable in frequency, and sometimes amplitude or frequency modulated with twice the mains frequency (100 Hz or 120 Hz);

2) Satellite TV receivers or LNAs. They produce a narrowband but relatively frequency-stable RF carrier that is usually not modulated and radiated via the satellite dish;

3) Unauthorized cellular repeaters (see § 6.3.3.1);

4) Jammers (see § 6.3.3.2);

5) GSM signals – If on the uplink frequency corresponding to the channel C0 of the affected base station signals can be received from GSM mobiles, although the affected base station is shut down, this is an indication of poor network planning. It means that another base station nearby uses the same C0 frequency which would be interpreted as interference by the affected base station.

Locating interference to a GSM base station is the most challenging task of all 3GPP technologies.

6.3.5 3G/UMTS

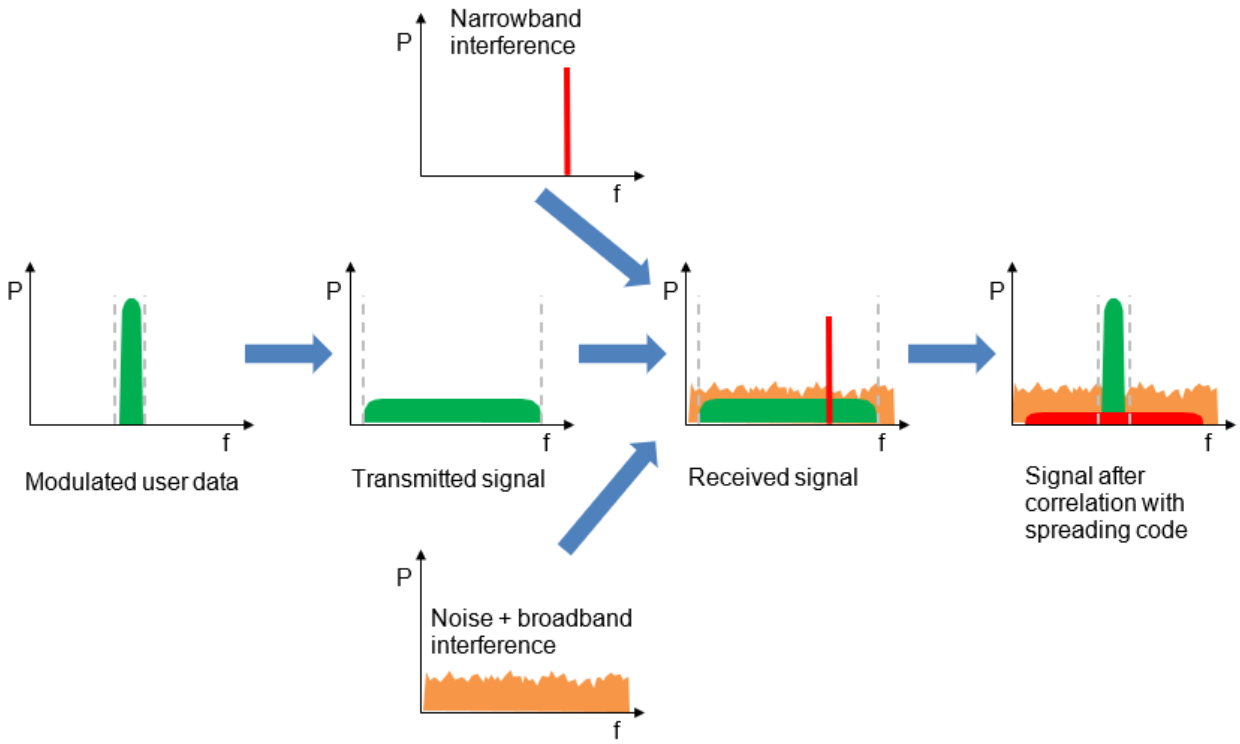
6.3.5.1 System description

The third generation of 3GPP technologies called "Universal Mobile Telecommunication System" (UMTS) was specifically designed to transport higher data rates than GSM, but speech calls are also possible. Also UMTS has seen enhancements to even raise the basic data rate such as HSDPA and HSUPA providing up to 14.4 Mbit/s in the downlink.

UMTS uses the spread spectrum technique to realize multiple access. This enables the base station to serve multiple UEs on one frequency at the same time. The user data is digitally modulated with a bit sequence called spreading code. This spreads the energy over a wide bandwidth when it is transmitted. The demodulation process on the receiver side, being principally the same process, collects the energy of the wanted user data into a narrowband signal again. All other signals, including noise and interference, remain wideband and can be filtered out. Figure 6-62 shows this principle.

FIGURE 6-62

Effects of spread spectrum technology in UMTS



The most important advantage of this technology is that all signals not being modulated with one of the unique spreading codes are largely suppressed at the receive side. This includes any interfering signals which makes the system relatively immune against interferers. A restriction of this technology is, however, that the signals from all UEs must reach the base station with roughly the same level. This requires a fast bidirectional channel on which the base station tells the UEs with how much power they have to transmit.

UMTS may be used in many frequency bands allocated to cellular systems, typically in the 900 and 2 100 MHz band.

Table 6-15 shows the relevant RF parameters of the UMTS technology.

TABLE 6-15

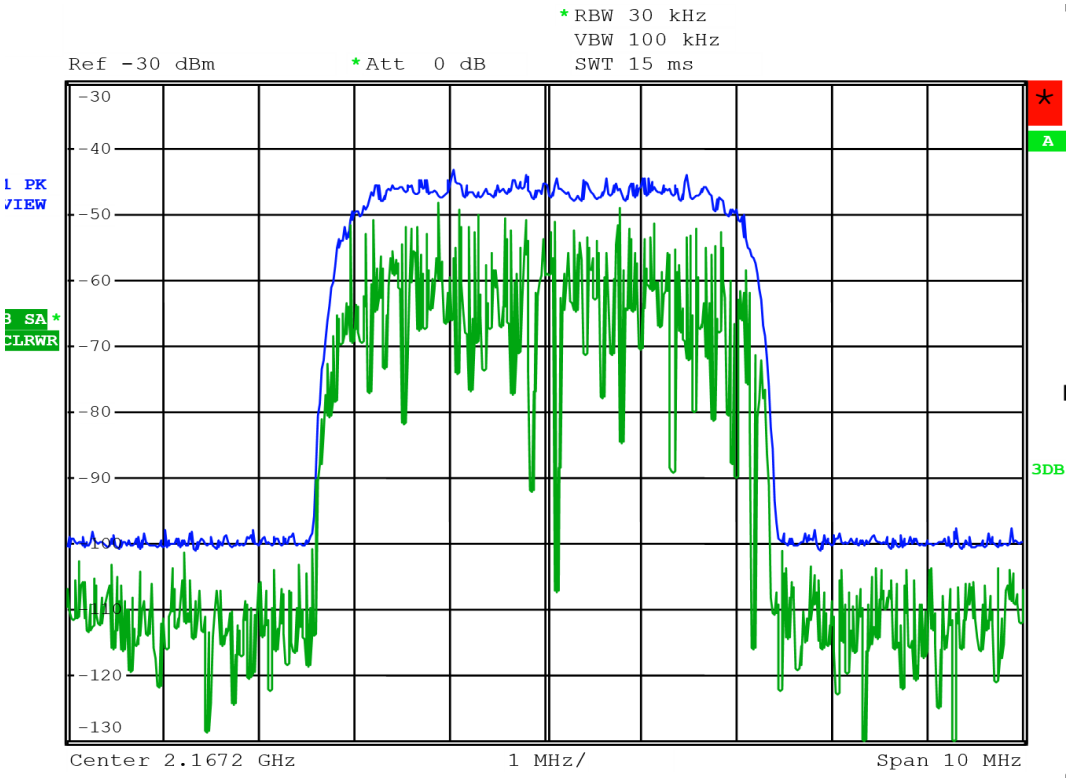
Relevant air interface characteristics of UMTS

Parameter	Value(s)
Modulation	QPSK (HCPA: up to 64QAM)
Symbol rate (chip rate) (Msymb/s)	3.84
Occupied bandwidth (MHz)	4.2
Channel spacing (MHz)	5
Multiple access	CDMA
Duplex method	FDD
Duplex spacing (e.g.)	45 MHz (900 MHz band) 95 MHz (1 800 MHz band) 190 MHz (2 100 MHz band)
Frame length (ms)	10

Figure 6-63 shows the Peak and RMS spectrum of a UMTS signal.

FIGURE 6-63

UMTS spectrum



6.3.5.2 Measurement of RF parameters

Identification of technology

Identification of a UMTS signal and separation from other cellular technologies is simple and can be done by displaying the ClearWrite or MaxHold spectrum of a channel with a spectrum analyser. Due to the fact that the channel spacing of 5 MHz is higher than the occupied bandwidth, it is also easy to separate adjacent channels.

Frequency and bandwidth

The centre frequency of a UMTS signal can easily be determined by using markers at each side of a recorded MaxHold spectrum and calculating the middle of both marker frequencies. The bandwidth can be measured using the OBW measurement function on the MaxHold recording, or by placing markers about 10 dB below the top level.

Level

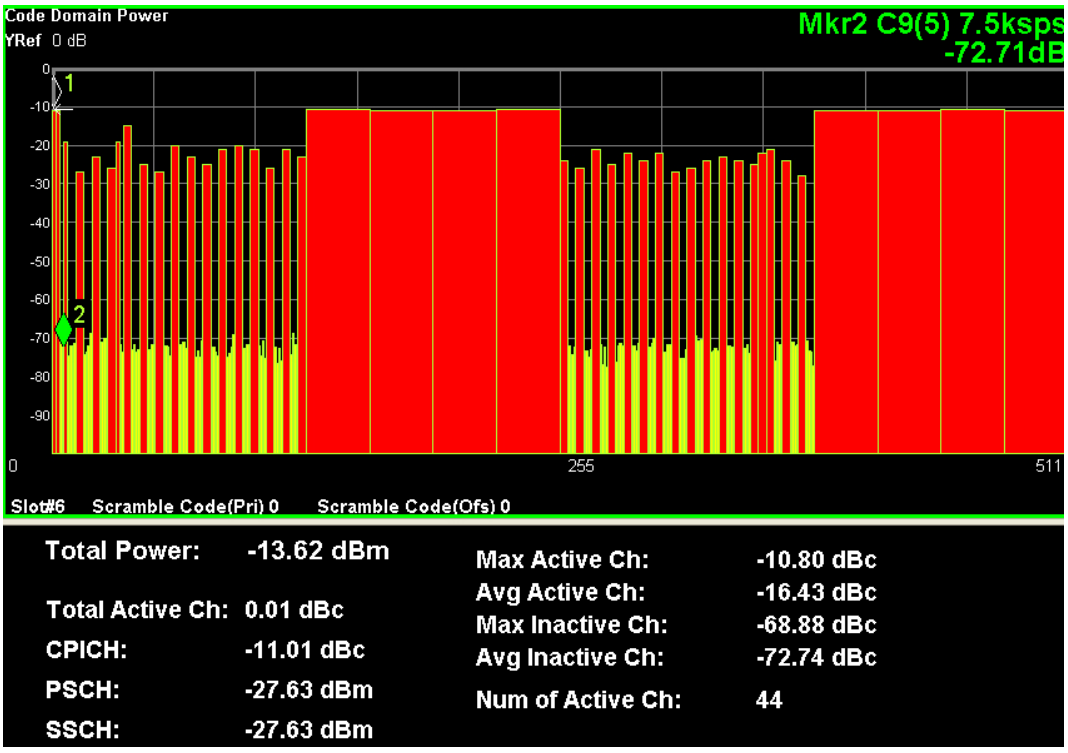
Due to the fact that the base station only transmits those logical channels that are currently needed to serve the UEs, the actual level of a UMTS base station depends on user traffic. The current level can be measured with a monitoring receiver or a spectrum analyser using the channel power function. The difference between peak and average level (CREST factor) of a UMTS signal also depends on user traffic and can range from 7 dB when the base station is fully loaded to 13 dB in idle mode.

Often, the maximum possible level of a UMTS base station has to be determined. This can only be measured in the so-called "code domain" which is the situation after de-spreading. In this domain, the level of each logical channel is separately shown. One of these channels is the Common Pilot and Information Channel (CPICH) where the broadcast information is constantly transmitted. The level of this traffic-independent channel can be used to extrapolate to a situation with full traffic load (i.e. full base station power), by adding a certain margin which is usually around 10 dB. So, a measured CPICH level of −90 dBm would result in a maximum possible base station level of −80 dBm.

For this measurement, dedicated measurement equipment capable of decoding the UMTS signal, is required. Figure 6-64 shows an example of such a code domain measurement.

FIGURE 6-64

UMTS code domain power measurement



In this example, the maximum possible power of the base station is −13.62 dBm, and the CPICH power is 11.01 dB less than the total power.

Section 6.3.2 provides other elements on common monitoring procedures.

6.3.5.3 Interference investigation

Information from the base station

Like all 3GPP technologies, UMTS base stations perform internal measurements of the interference level. This information should be requested from the operator reporting interference. In UMTS, measurement of the remaining wideband level after dispreading/correlation with the used spreading code in the corresponding uplink band takes place. This is called "Received Total Wideband Power" (RTWP). It is measured in dBm. Table 6-16 gives guidance on the interpretation of the RTWP values reported by the base station.

TABLE 6-16

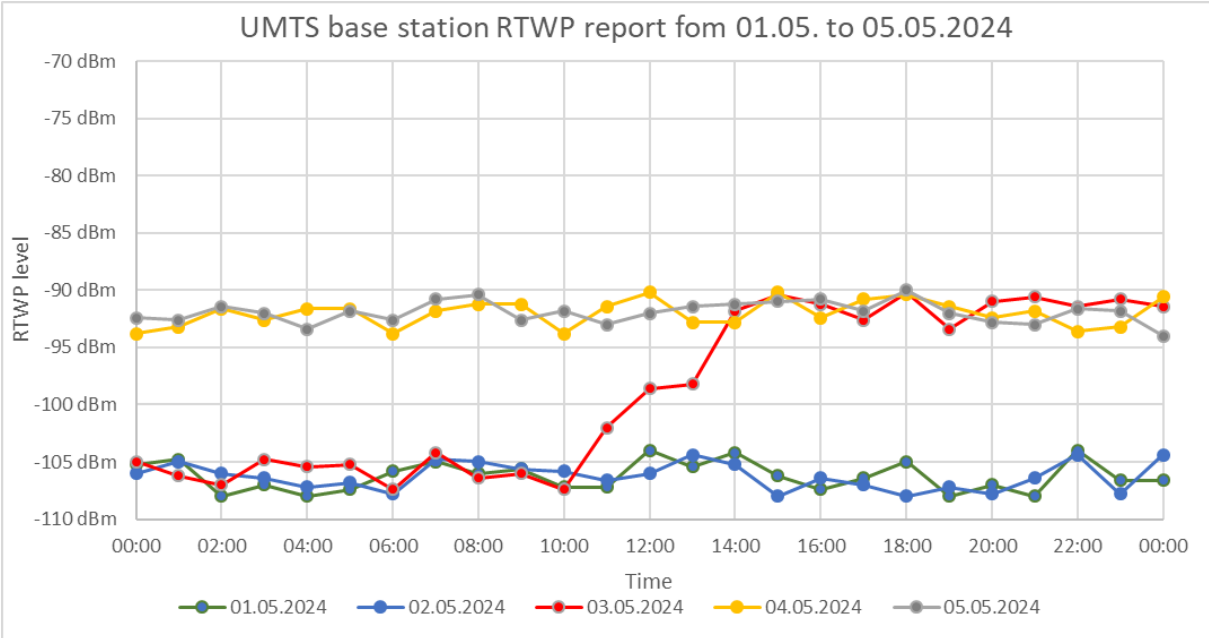
UMTS RTWP interference levels

RTWP value	Interpretation
<−106 dBm	Quiet zones, no interference
−106 dBm to −102 dBm	Normal for city regions, not necessarily interference
−102 dBm to −100 dBm	Possible weak interference
−100 dBm to −90 dBm	Medium interference
> −90 dBm	Strong or permanent interference

Figure 6-65 shows an example of a UMTS interference history as reported by the base station.

FIGURE 6-65

UMTS base station interference report (example)



This example shows a permanent interference starting at 03.05.2024 around noon. The interference level is around −90 dBm in 5 MHz bandwidth at the base station antenna.

Recommended procedure

As described above, UMTS is relatively immune against interference. The wanted signal can even be below interfering signals and is still decodable. This means when investigating the received signal with a spectrum analyser, narrowband interfering signals must clearly peak out of the wanted signals. If they are not visible, they cannot cause noticeable interference to the base station. Broadband interference is visible beyond the channel edges or in the gaps between channels. When following the general procedure described in § 6.3.2 above, the following specialties for UMTS apply:

1) Do not shut down the affected base station. It has to be operable during interference investigation. This is necessary to prevent nearby UEs to log on to the next base station further away, requiring a high transmit power. In that case, their signal would mask any interfering signal at the affected base station.

2) In order not to be overloaded by the downlink signal from the affected base station, off-air measurements with the monitoring equipment have to be done with a filter in front of the monitoring receiver or spectrum analyser. This can be a low-pass with a cut-off frequency at the upper band edge of the uplink band, or a band pass filter tuned to the uplink band.

3) Measurement at the affected sector antenna of the base station, while it is in operation can be done by shutting it down, then connecting the monitoring equipment to one of the two polarization planes of the base station antenna, and then powering up the base station again. After issuing an error message about one antenna port not being connected, it will work on one polarization plane only. However, due to the fact that the base station measures RTWP after dispreading, interference levels measured with monitoring equipment will not match the levels reported by the base station.

Common interferers

1) Amplifiers from active TV antennas, satellite TV receivers or LNAs, especially in the 900 MHz band. They usually produce a narrowband carrier.

2) Unauthorized cellular repeaters (see § 6.3.3.1).

3) Jammers (see § 6.3.3.2).

4) Faulty DECT stations or imported DECT 6.0 devices in the 1 900 MHz uplink bands outside North America. They produce a pulsed signal with 10 ms repetition rate and a bandwidth slightly above 1 MHz.

5) RLAN routers / modems working in the 2.4 GHz ISM band. Their sideband emissions may produce an irregular pulsed emission in the 1 900 MHz UMTS uplink band.

Due to the immunity of UMTS against interference and the signal spreading effects, UMTS interference is the easiest to investigate among all 3GPP technologies.

6.3.6 4G/LTE

6.3.6.1 System description

LTE is the successor of UMTS and provides even higher data rates and better spectrum efficiency. For this reason, UMTS systems are being replaced by LTE in more and more countries. LTE uses OFDM modulation with very flexible RF parameters. The standard defines different bandwidths and subcarrier modulation. Multiple access to a downlink channel is realized by allocating a subset of carriers for a flexible amount of time to each user. A so-called scheduler determines when and how long each user gets a specific part of the available bandwidth. This access method is called “Orthogonal Frequency Division Multiple Access” (OFDMA). The result is a very dynamic RF spectrum with constantly changing bandwidth and power. LTE is now used in all frequency bands allocated to public mobile services.

Table 6-17 shows typical relevant RF parameters of the LTE signal.

TABLE 6-17

Typical air interface characteristics of LTE

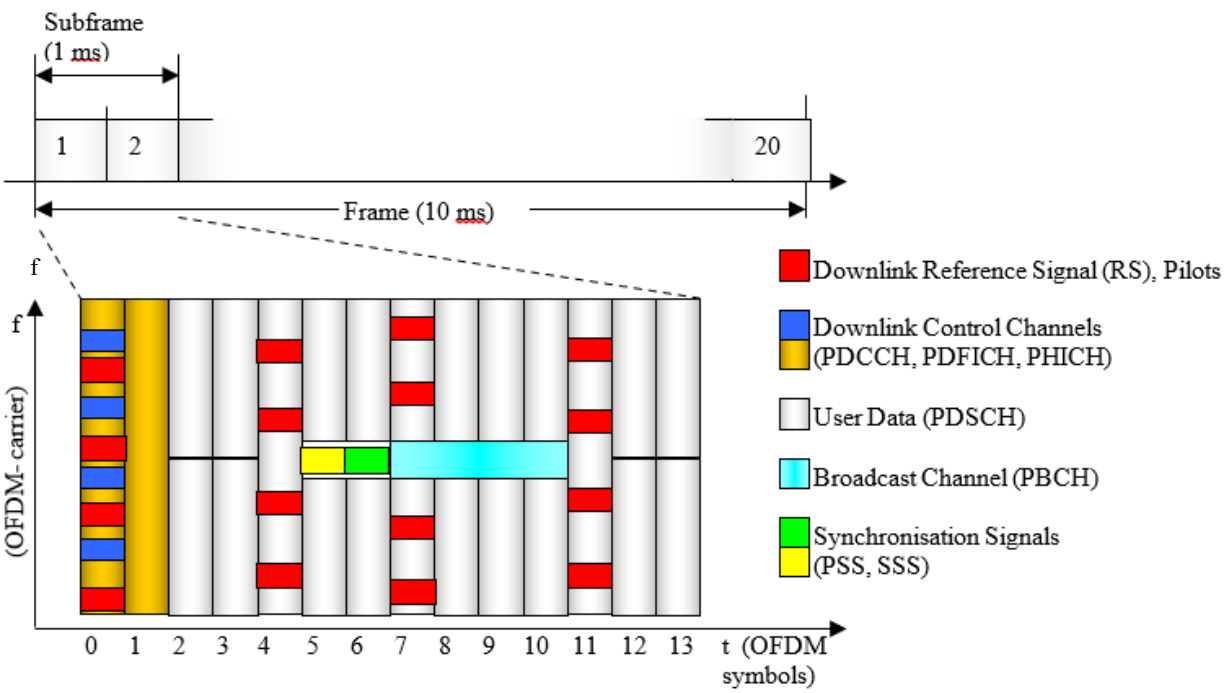
Parameter	Value(s)
Modulation	Main carrier: OFDM Sub-carriers: QPSK, up to 256QAM
Subcarrier spacing (kHz)	15
Channel width (MHz)	1.4 / 3 / 5 / 10 / 15 / 20
Symbol length (µs)	71.4
Multiple access	Downlink: OFDMA, Uplink: SC-FDMA
Duplex method	FDD or TDD
Duplex spacing (e.g.)	Variable
Frame length (ms)	10
Resource block	12 OFDM carriers for 0.5 ms length

Time division duplex is most common in the 2.3 GHz, 2.6 GHz and 3.5 GHz bands. In paired bands that were previously used by older technologies, FDD is used also for LTE.

Like all 3GPP systems, LTE also transmits broadcast and synchronisation signals that can be used for measurements. They occupy the centre 1.08 MHz of an LTE channel, and are transmitted every 10 ms. Figure 6-66 shows the principle frame structure.

FIGURE 6-66

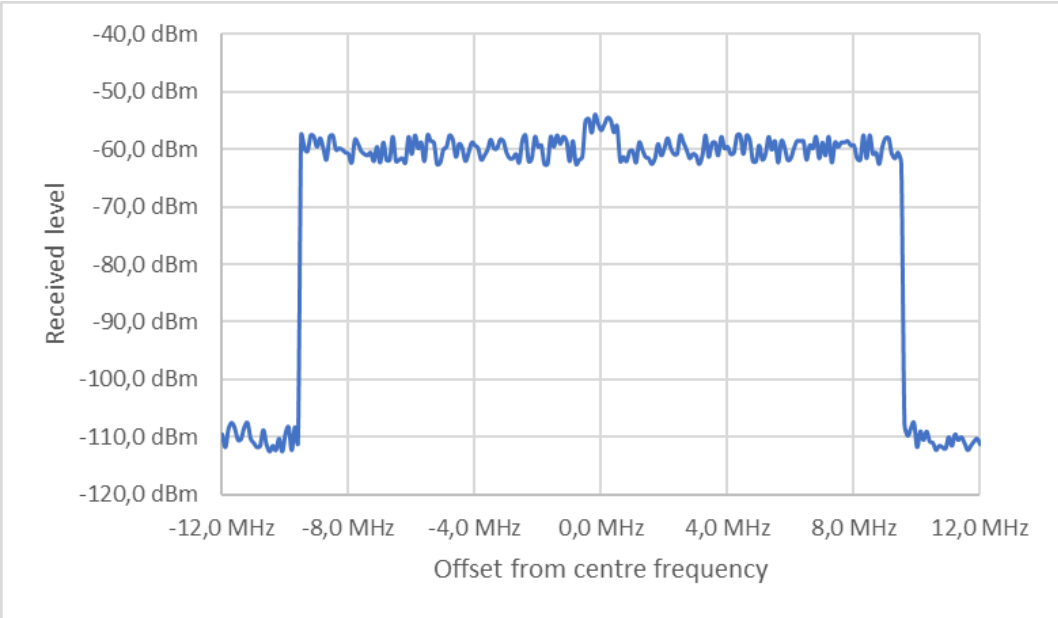
LTE downlink frame structure



In a MaxHold spectrum of the downlink, the broadcast channel often has a slightly higher spectral level than the other channels. Figure 6-67 shows an example for a 20 MHz LTE channel.

FIGURE 6-67

Typical MaxHold Spectrum of an LTE base station



6.3.6.2 Measurement of RF parameters

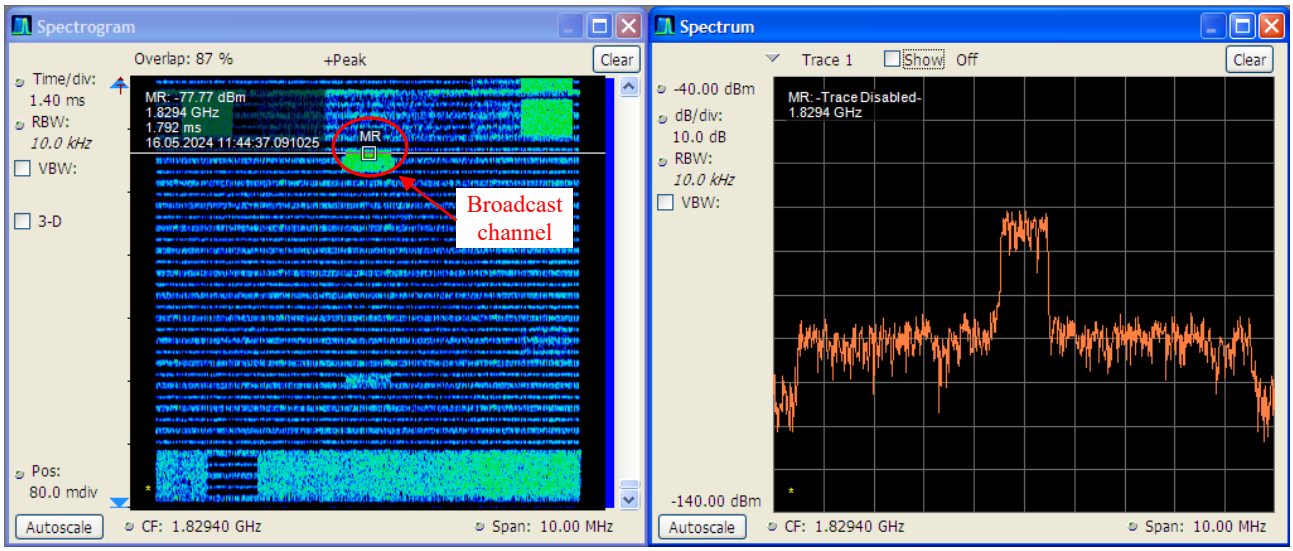
Identification of technology

The typical rectangular spectrum of an LTE signal, when recorded MaxHold, already distinguishes this signal from all previous 3GPP technologies. However, it is sometimes not easy to distinguish it from a 5G NR signal which is described in § 6.3.7 below. On indication of an LTE signal is the characteristic broadcast channel that is often visible in the MaxHold spectrum. It is always in the channel centre and 1.08 MHz wide. If the cell is fully loaded with traffic, a ClearWrite spectrum recorded at the right time might better show the PBCH.

A more unambiguous way to identify LTE is using a realtime spectrum analyser that is able to show the spectrogram like in the example in Fig. 6-68.

FIGURE 6-68

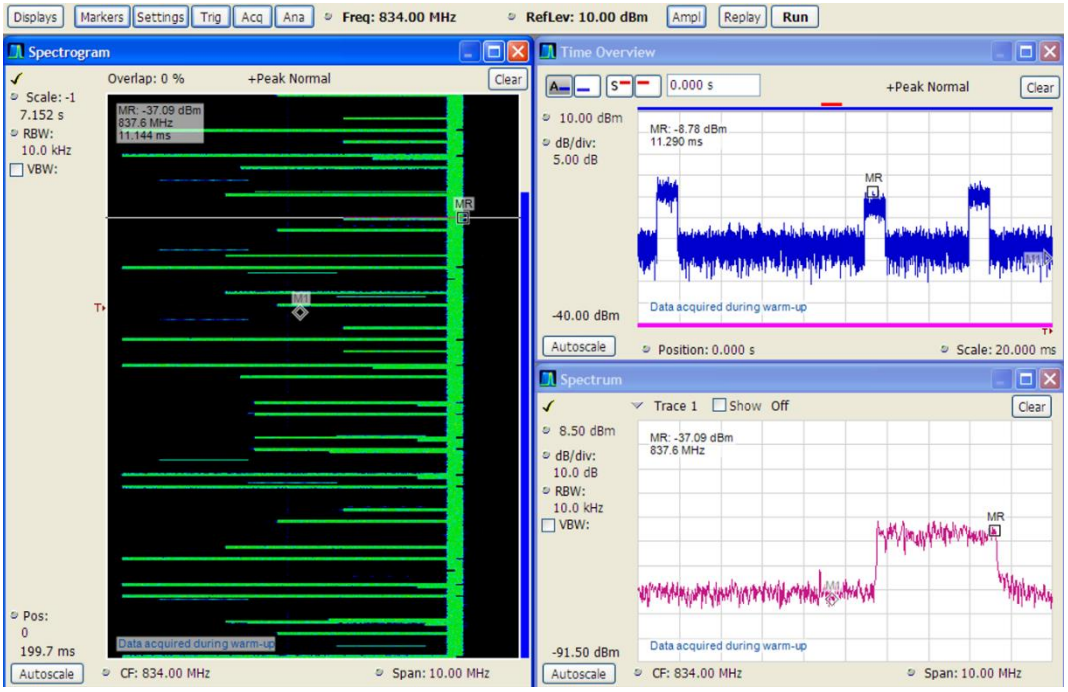
Analysis of an LTE downlink signal on a realtime spectrum analyser



LTE uplink signals also use OFDM as the primary modulation. The difference to downlink signals is that they have a narrowband control channel either on one end of the channel or alternating on the lower and upper channel edge. Furthermore, the occupied bandwidth of their data emissions always starts at the position of the control channel. Figure 6-69 shows a typical example.

FIGURE 6-69

Analysis of an LTE uplink signal on a realtime spectrum analyser



Frequency and bandwidth

The centre frequency of an LTE signal is best measured by recording the MaxHold spectrum and setting markers to the edges of the rectangular spectrum. The centre frequency is the middle of both markers. It is about 10 to 20% less than the assigned channel width.

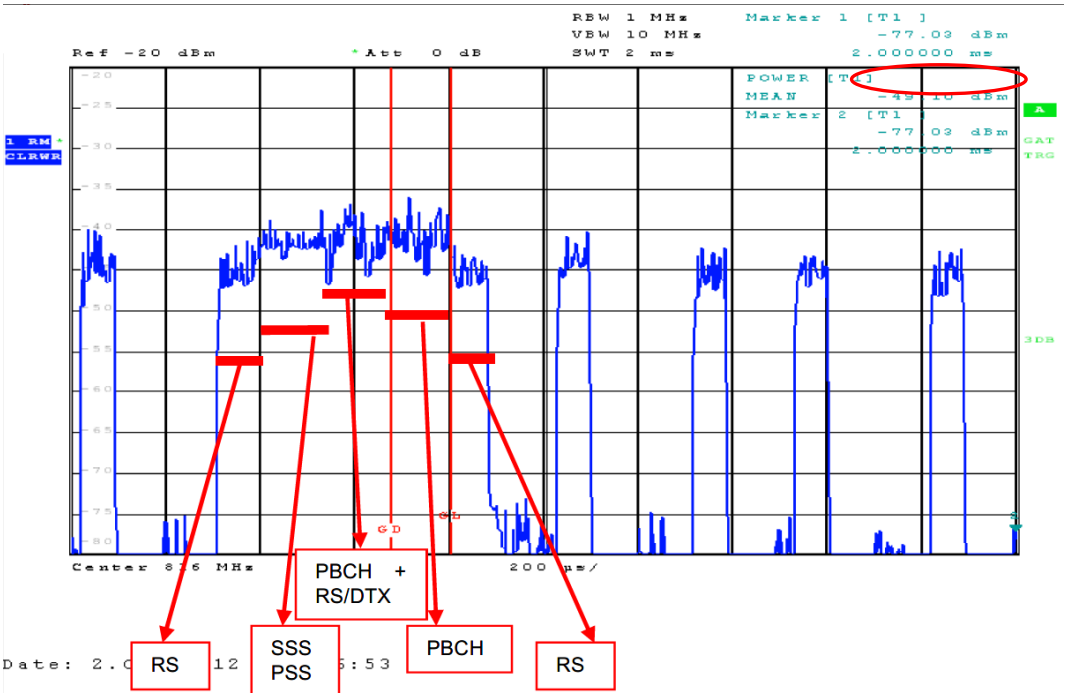
Level

Due to the fact that the base station only transmits those resource blocks that are currently necessary to serve the UEs, the actual level of an LTE base station depends on user traffic and is constantly changing. The current level can be measured with a monitoring receiver or a spectrum analyser using the channel power function. The difference between peak and average level (CREST factor) of an LTE signal also depends on user traffic, but is normally not less than 10 dB in case the base station is fully loaded.

Often, the maximum possible level of an LTE base station has to be determined. This is possible by measuring the level of the broadcast channel and extrapolate it to a situation with maximum traffic. Measurement of the broadcast channel, however, requires equipment that can do a triggered or gated power measurement. The receiver/analyser is tuned to the centre frequency of the LTE channel with a bandwidth of around 1 MHz. In a time domain display, the limits for the power measurement may be set, e.g. with markers. Figure 6-70 shows an example of such a time domain power measurement.

FIGURE 6-70

Measurement of the LTE broadcast signal



The measurement time is limited to the time between the red vertical lines. The result is shown in the red circle.

Extrapolation of the measurement result to a situation with full traffic load can be done with the following formula:

$$P_{max} = P_{meas} + 10 * \log(\frac{Meas_{Bw}}{Channel_{Bw}})$$

with:

P_{max} : Extrapolated maximum received power with full traffic in dBm

P_{meas} : Measured level of the PBCH in measurement bandwidth in dBm

$Meas_{Bw}$: Measurement bandwidth in MHz (recommended: 1 MHz)

$Channel_{Bw}$: Bandwidth of the LTE channel in MHz.

Section 6.3.2 provides other elements on common monitoring procedures.

6.3.6.3 Interference investigation

Information from the base station

Like all 3GPP technologies, LTE base stations perform internal measurements of the interference level. This information should be requested from the operator reporting interference. In LTE, measurement of the received level in each unused resource block of the uplink channel or time slot is measured and averaged over a certain time, usually 15 minutes. The key parameter used to assess uplink interference is the Received Interference Power (RIP), as defined in 3GPP TS 36.214 (2025-07). Table 6-18 provides guidance on the interpretation of the measured interference levels.

TABLE 6-18

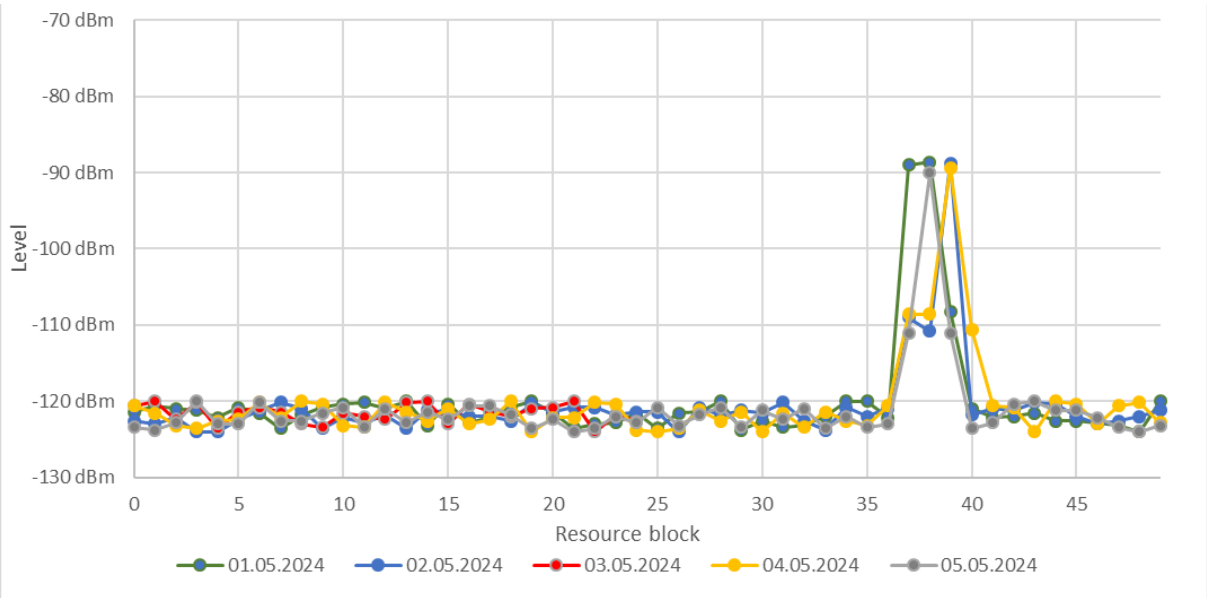
LTE uplink interference levels

ULinterference_avg	Interpretation
<−124 dBm	No interference
−124 dBm to −115 dBm	Light to medium interference
> −115 dBm	Strong interference

The measured interference level is presented for each frequency inside the channel bandwidth separately. This results in a graph where the interference level is shown against physical resource block (PRB) frequency, so that it resembles a display of the interfering signal much like from a spectrum analyser. Figure 6-71 shows an example of such an interference report.

FIGURE 6-71

LTE base station uplink interference average (example)

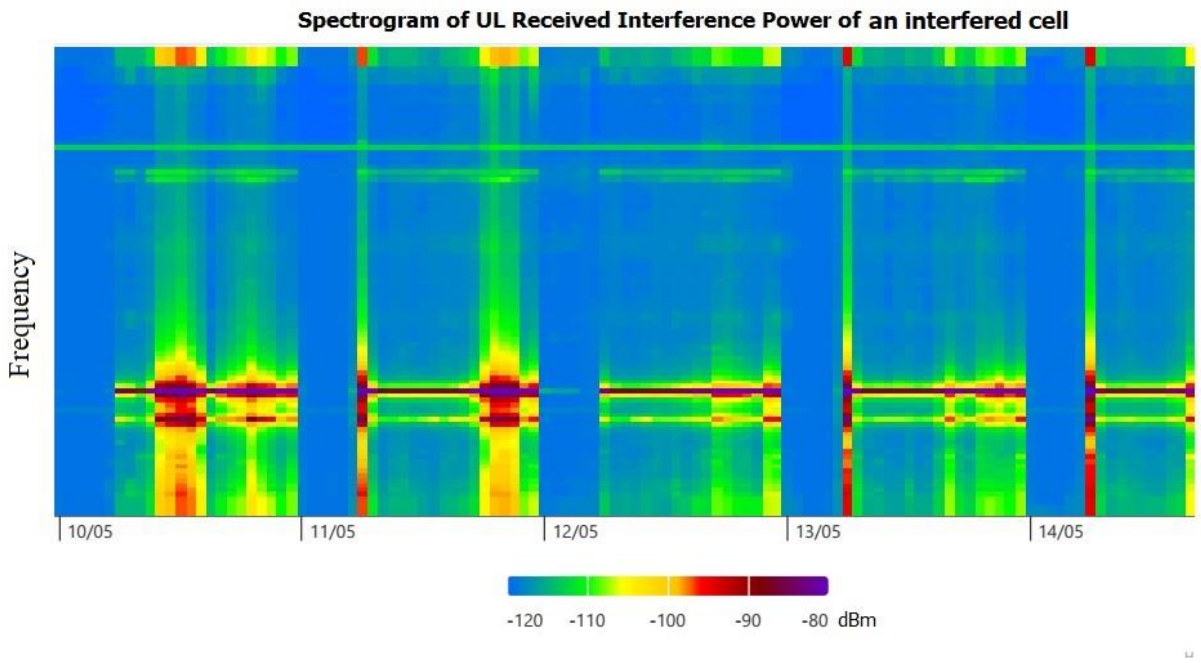


This example shows a narrowband interfering signal being instable in frequency, interfering resource blocks 36 to 39. The constant level indicates that the interference was continuously present at least during the evaluation time from 01.05.2024 to 05.05.2024.

With self-developed procedures/tools that allow direct connection to the operator's database with internal BS measurements, additional representations of the interference situation are possible, such as the spectrogram shown in Fig. 6-72.

FIGURE 6-72

LTE-700 MHz uplink interference spectrogram (example)



Recommended procedure

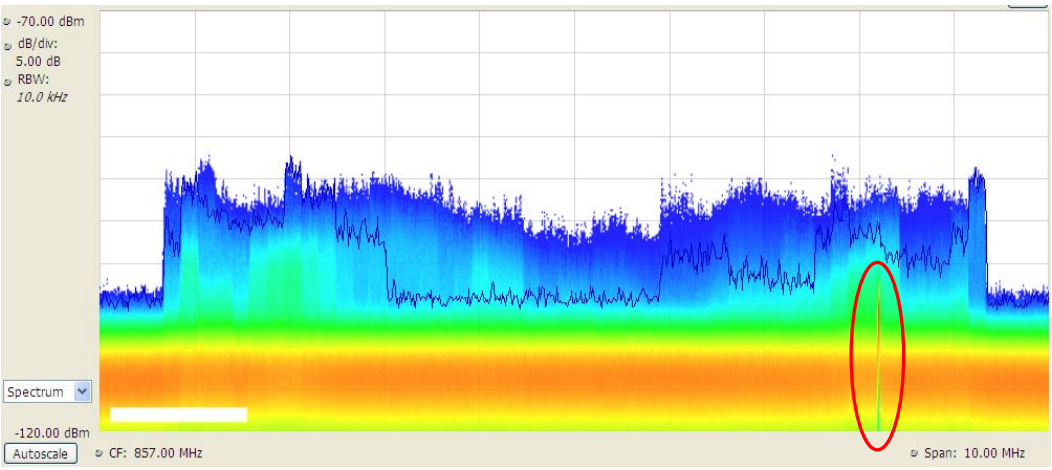
When following the general procedure described in § 6.3.2 above, the following specialties for LTE apply:

1) If possible, shut down the affected base station. This is necessary to receive the interfering signal without being masked by signals from served UEs.

2) In FDD systems the uplink band may still be filled with signals from UEs served by nearby LTE base stations. This is unavoidable and makes it recommendable to observe the spectrum with a receiver/realtime analyser that can create a spectrum display showing the spectral levels together with their probability in different colours. Nearly each equipment manufacturer has a different name for this display, for example “phosphor display”, “realtime spectrum”, “persistence spectrum”, or “DPX display”. The advantage of this type of spectrum display is that it is possible to spot weak signals in a spectrum that are masked by much stronger signals, if both have different time behaviour. Figure 6-73 shows an example of such a display where a narrowband signal is visible beneath the much stronger LTE signal. To improve the sensitivity of the receiver/realtime analyser, the use of band pass filters tuned to the uplink band is recommended.

FIGURE 6-73

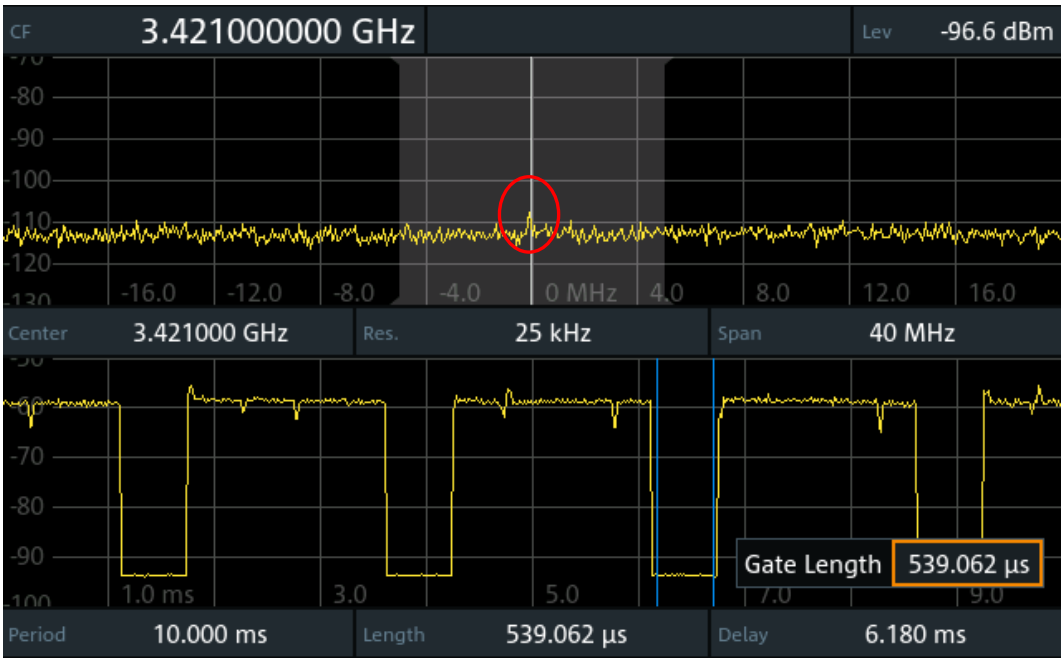
Example of a persistence spectrum display with interfering carrier



In TDD systems, the uplink signals from nearby UEs can be eliminated by using equipment that can do a triggered or gated measurement, showing time and frequency domain simultaneously. The receiver/analyser is tuned to the frequency of the interfering carrier with a bandwidth/span of several MHz. In a time domain display, the limits for the spectrum measurement may be set, e.g. with markers. Figure 6-74 shows an example of such a combination. Although being very weak in level, the interferer is clearly visible in the spectrum (red circle).

FIGURE 6-74

Example of a gated spectrum display with interfering carrier



Because of the presence of uplink signals from nearby UEs it may be quite challenging to measure the actual interference level, especially in FDD systems. Comparing interference levels obtained by monitoring receiver/analyser with those reported by the base station is only valid when measured with 15 kHz IF bandwidth or RBW, and at a time where the particular resource block is not masked by a signal from a UE.

Common interferers

1) Amplifiers from active TV antennas, Satellite TV receivers or LNAs, especially in the 700, 800 and 900 MHz bands. They usually produce a narrowband carrier.
2) Unauthorized cellular repeaters (see § 6.3.3.1).
3) Jammers (see § 6.3.3.2).
4) In the 2.6 GHz and 3.5 GHz band, there is very little probability of interfering devices. Mostly, interference comes from other/faulty LTE base stations in the same band, or on adjacent channels causing unwanted emissions.
5) Interference caused by emissions from other technologies in the same band, especially FDD technologies, or from LTE networks not being time synchronized with the affected network. This problem arises especially in border regions when there is no common agreement between operators in both countries concerning the cellular technology used.

6.3.7 5G/NR

6.3.7.1 System description

5G/New Radio (NR) is the latest development of 3GPP cellular systems at the publication of this Handbook. This technology offers even higher data rates and is used in even higher frequency bands. These are separated in frequency range (FR) 1 up to 7.125 GHz, and FR2 for frequencies above 24.25 GHz, called "millimetre waves". 5G technology is installed at locations equipped with LTE. In the so-called "non-standalone" mode (NSA), the UE establishes a connection via LTE and the 5G technology is switched on to provide additional download capacity if desired. In the "standalone" mode, the UE communicates only via 5G. It depends on the capabilities of the UE and the configuration of the network which mode is available. In addition to the high data rates, the 5G SA mode offers extremely short latencies of the network which allows new applications such as remote control of equipment to be realized over cellular networks.

To enable maximum adaptation to the RF environment and user demands, even more of the relevant RF parameters are flexible in the 3GPP standard for 5G NR. Like LTE, the main RF carrier modulation and multiple access in the downlink is OFDMA, the uplink uses SC-FDMA, and access to RF resources is realized by allocating resource blocks (RBs) to mobiles by a scheduler. Depending on the band allocation, duplex can be realized with FDD and TDD.

Table 6-19 shows typical relevant RF parameters of the 5G NR signal in the most common frequency range below 7.125 GHz (FR1).

TABLE 6-19

Typical air interface characteristics of 5G NR in FR1

Parameter	Value(s)
Modulation	Main carrier: OFDM Sub-carriers: 256QAM
Subcarrier spacing (kHz)	15, 30 or 60
Channel width (MHz)	5/10/15/20/25/40/50/60/80/100
Symbol length (µs)	66.7 / 33.3 / 16.7
Multiple access	Downlink: OFDMA, Uplink: SC-FDMA
Duplex method	FDD or TDD
Duplex spacing (e.g.)	(variable)
Frame length (ms)	10, 20 or 40
Resource block	12 OFDM carriers for 1 ms length

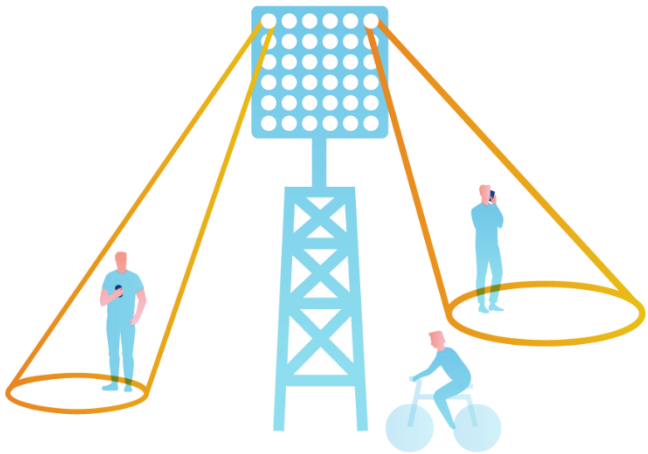
In FR2, bandwidths of up to 800 MHz are defined.

Time division duplex is most common in the 2.3 GHz, 2.6 GHz and 3.5 GHz bands. In paired bands that were previously used by older technologies, FDD is used also for 5G NR.

Especially in bands above 2.3 GHz, 5G NR base stations commonly use active antenna systems (AAS). The antenna consists of a rectangular array of multiple dipoles, each one having its own transmitter unit. This technology enables flexible antenna patterns both in gain and direction. The base station can point a beam into a specific direction instead of spreading all energy over the whole 120 degrees of a sector. This principle is called beam forming. It is even possible to create multiple beams into different directions simultaneously and follow a moving UE. Figure 6-75 illustrates beamforming.

FIGURE 6-75

Beam forming by a 5G NR base station with AAS



Like LTE, 5G NR also transmits broadcast information once every frame. However, in FR1, the bandwidth of the broadcast block is 3.6 MHz or 7.2 MHz, and it is not necessarily in the centre of the channel. The broadcast information is transmitted together with synchronisation signals in a so-called "synchronization and signalling block" (SSB). A base station with AAS can be configured to transmit up to 8 SSBs in a frame, one after the other, into different directions. Figure 6-76 shows an example with 7 SSBs.

FIGURE 6-76

Example of a 5G NR base station with 7 SSBs

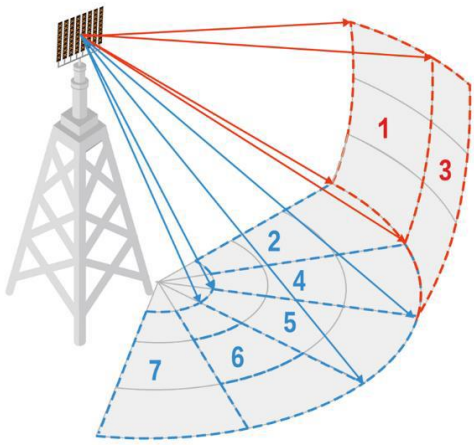
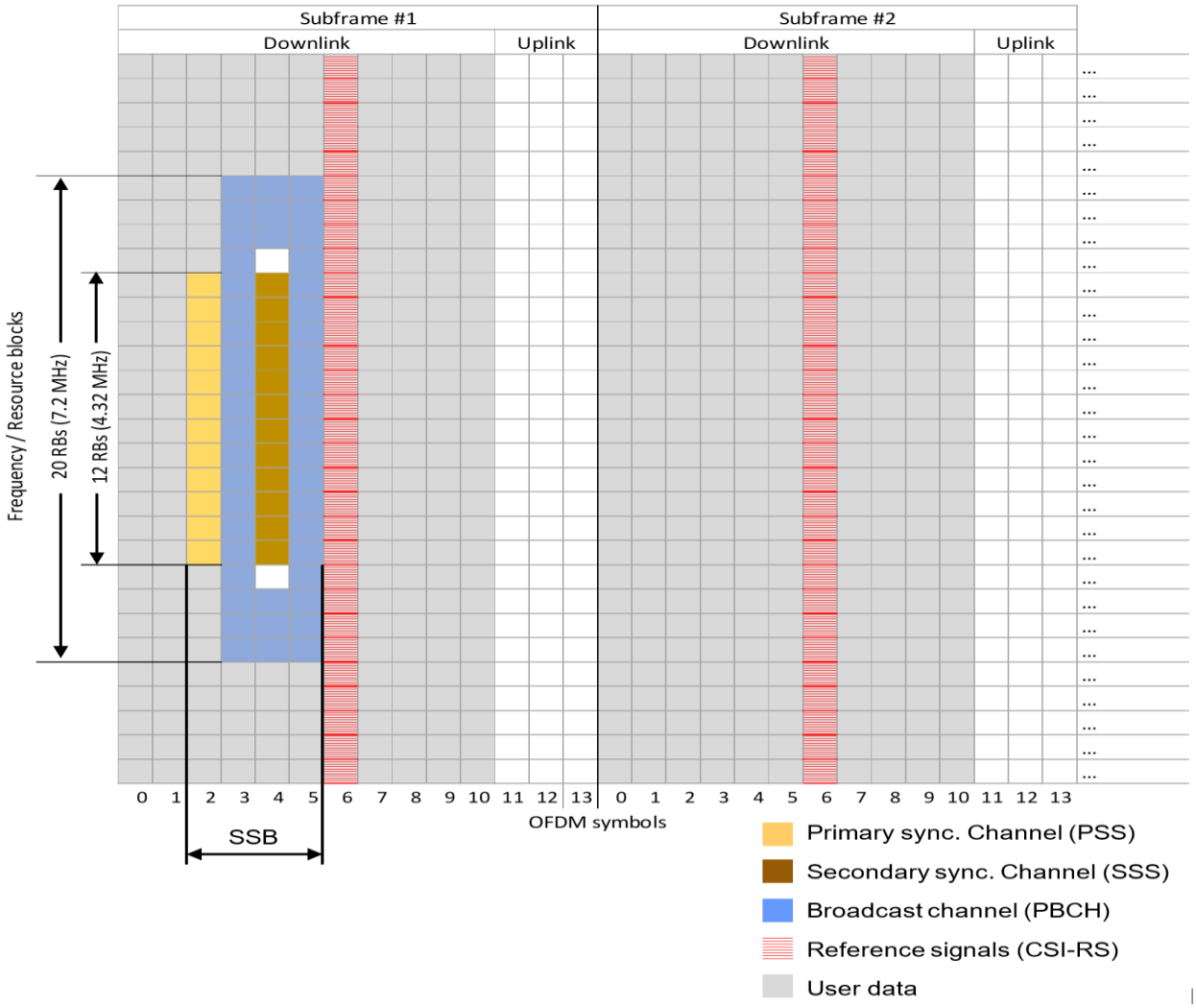


Figure 6-77 shows the principle structure of a 5G NR subframe in time and frequency domain. In this example, the station is configured for 1 SSB, which is centred in the RF channel.

FIGURE 6-77

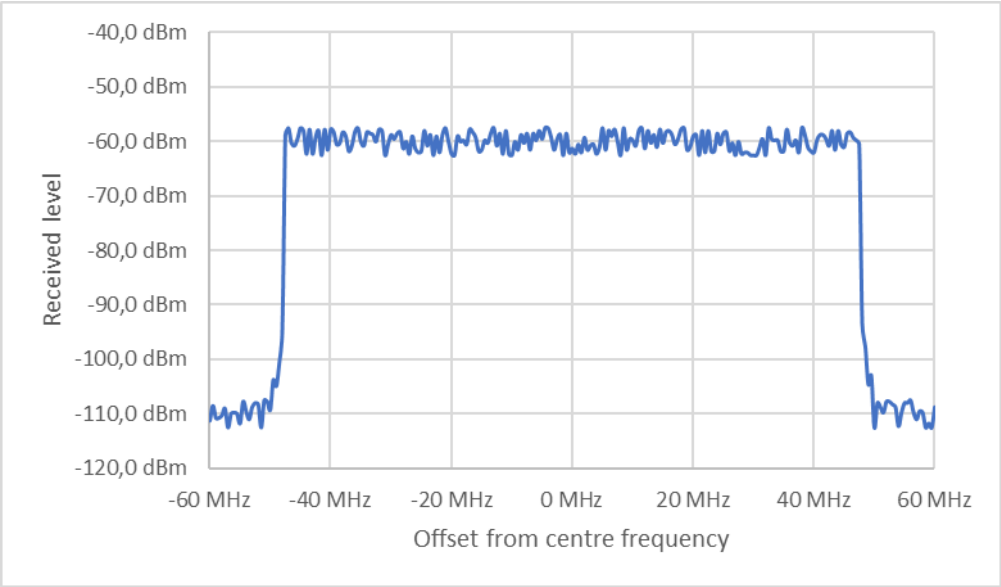
Example structure of a 5G NR subframe structure



Like LTE, 5G NR produces a highly dynamic spectrum. The MaxHold spectrum in FR1 is rectangular after sufficiently long integration time, as shown in Fig. 6-78.

FIGURE 6-78

MaxHold spectrum of a 5G NR downlink signal in FR1 (example)



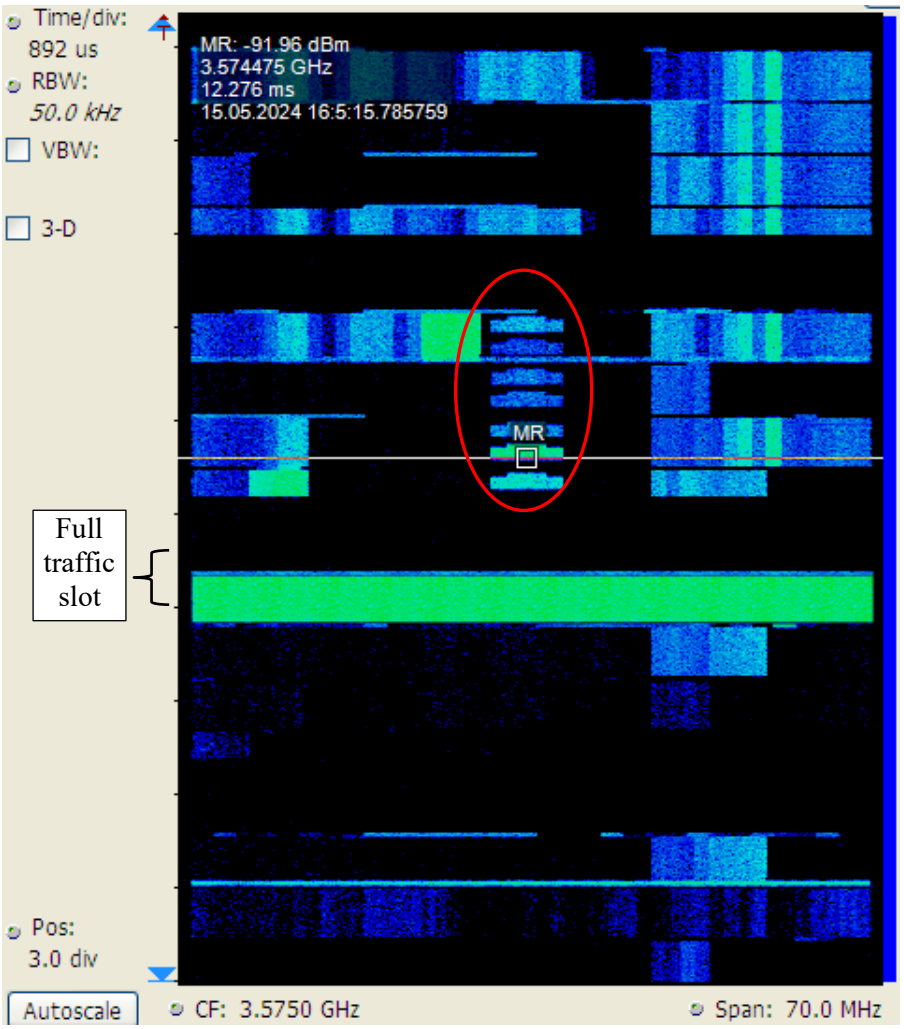
6.3.7.2 Measurement of RF parameters

Identification of technology

Like LTE, the spectrum of a 5G NR base station is principally rectangular. Unlike LTE, however, the broadcast channel (SSB) is normally not visible in the MaxHold spectrum. If the bandwidth is higher than 20 MHz, then it can only be a 5G NR signal. For bandwidths up to 20 MHz, the distinction between LTE and 5G NR could only be made with a realtime spectrum analyser capable of showing a spectrogram, like in Fig. 6-79.

FIGURE 6-79

Spectrogram of a 5G NR downlink signal in FR1 (example)



In this example, the base station was configured for 7 SSBs (red circle).

Frequency and bandwidth

The centre frequency of a 5G NR signal is best measured by recording the MaxHold spectrum and setting markers to the edges of the rectangular spectrum. The centre frequency is the middle of both markers. It is about 10 to 20% less than the assigned channel width.

Level

Like LTE and UMTS, the momentary level of a 5G NR base station varies with traffic. If AAS is used, this dynamic is even increased by the fact that not all signals are transmitted in the direction of the measurement position. The momentary level can be measured with a spectrum analyser using the channel power function, together with the RMS detector.

In many cases it is necessary to determine the maximum possible level at a specific location under a full traffic situation. If the base station uses a passive antenna, the SSB is measured with the gated or triggered measurement in the time domain as described for LTE in § 6.3.5.2. Only the measurement has to be done on the centre frequency of the SSB which has to be determined before. Extrapolation from the measurement result to full traffic is also equal to LTE.

If the base station uses AAS, however, measurement of the maximum level is only possible directly on a traffic beam. This can be achieved by attracting a traffic beam using a UE near the measurement location that performs a download. A realtime analyser is necessary to determine in the spectrogram which time slots were allocated to our UE, and limiting the level measurement time to that time slot only. Preferably, time slots should be selected where our UE got the whole channel width, like the slot marked "Traffic" in the middle of Fig. 6-78. In that case, the measurement result can be taken directly as no further extrapolation to a full traffic situation is required.

Total radiated power (TRP)

Usually, 5G NR stations using AAS do not have an RF port accessible for measurements because amplifiers and antenna elements form one combined unit. Regulatory limits that are normally to be measured at the transmitter output are therefore defined as total radiated power (TRP). This is equivalent to the forward RF power supplied to the antenna and thus ensures that AAS stations are treated equal to stations using passive antennas.

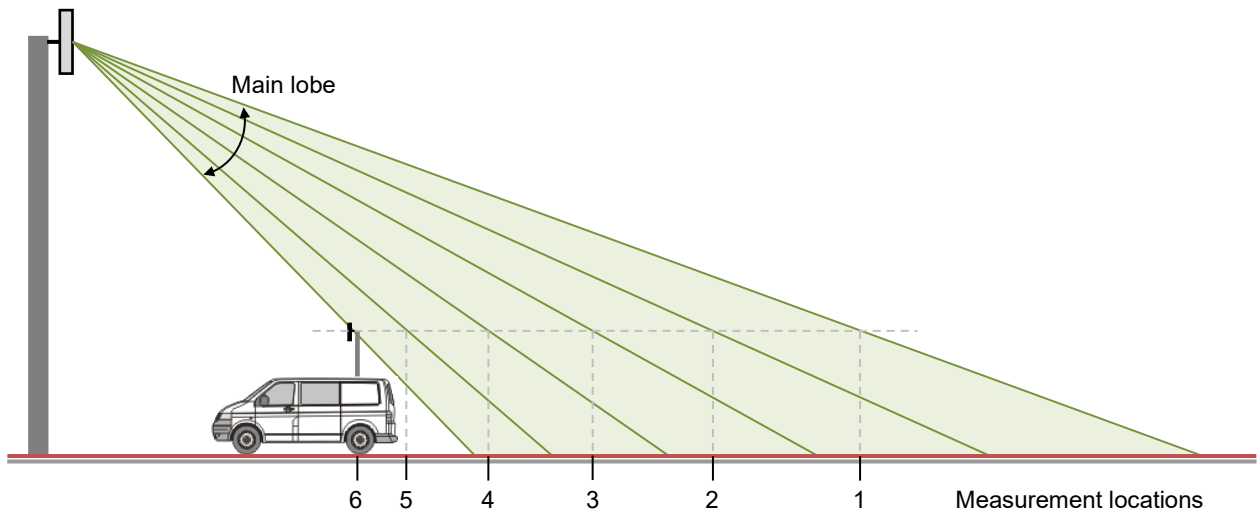
The exact TRP can only be calculated from measurements made off-air. Without a-priori information on antenna gain and directivity, all field strength levels integrated over the whole sphere around the antenna would have to be measured. Even with drones this is not entirely possible for installations in the field. However, a fair estimation of the TRP can be derived from measurements of the main lobe region of a beam. This is possible because common gains of 5G NR beams are in the range of 15 to 25 dBi, so that all energy transmitted in side lobes may be neglected. Setup and equipment are equal as described for measurements of the maximum possible level above.

When no a-priori information about gain and directivity of the different beams is available, a traffic beam has to be attracted to a suitable measurement position by a UE. Ideally, a drone equipped with a realtime analyser is used to cover the 3D angle region of the main traffic beam. The results taken at equidistant angles are then integrated and translated into radiated power according to the principles described in § 7.3.4.

If no measurement drone is available and the area where the main lobe touches the ground is accessible, these measurements could also be done using mobile or portable monitoring equipment. The principle is described in ECC Report 345. However, the measurement distance for each location is different as shown in Fig. 6-80. Therefore, calculation of the radiated power has to be done separately for each measurement point prior to integration.

FIGURE 6-80

Measurement of TRP from a 5G NR base station with mobile equipment



If the gain of the SSB or traffic beam is known, it is sufficient to measure the field strength at a location in the centre of that beam. From the result, the e.i.r.p. can be calculated according to the formulae given in § 7.3.2. Because of the fact that the gain of 5G NR station antennas is usually higher than 20 dBi, the e.i.r.p. can be set equal to the TRP and all energy transmitted in side lobes can be neglected.

Section 6.3.2 provides other elements on common monitoring procedures.

6.3.7.3 Interference assessment

Interference assessment follows the same procedures as described in § 6.3.6.3 for LTE. Also, 5G NR base stations perform measurements on unused resource blocks which can be evaluated in the same way as in Fig. 6-71. Interpretation of the interference levels are equal to the values given in Table 6-19. Like in LTE systems, comparing interference levels obtained by monitoring receiver/analyser with those reported by the base station is only valid when measured with an IF bandwidth or RBW that matches the subcarrier spacing (15, 30 or 60 kHz), and at a time where the particular resource block is not masked by a signal from a UE.

For investigating interferences in 5G systems it is advisable to use measurement equipment capable of capturing the whole channel width at once, which can be as high as 100 MHz in FR1. Fast panorama scans can be performed during the time gate to reliably detect interferences within signal bandwidths wider than the realtime capability of the receiver/analyser.

Many common interference sources are also the same as described for LTE, because 5G NR principally uses the same frequency bands. For FR2, no experience on common interference sources has been gained at publication of this handbook.

One interference scenario, however, is occurring especially bands above 2 GHz where Time Division Duplex (TDD) is commonly used by 5G NR and also LTE systems: Interference from downlink signals arriving in the uplink time slot of the victim system. The cause of this interference may be:

– Unsynchronized base stations within the victim network or a network in a neighbouring country;

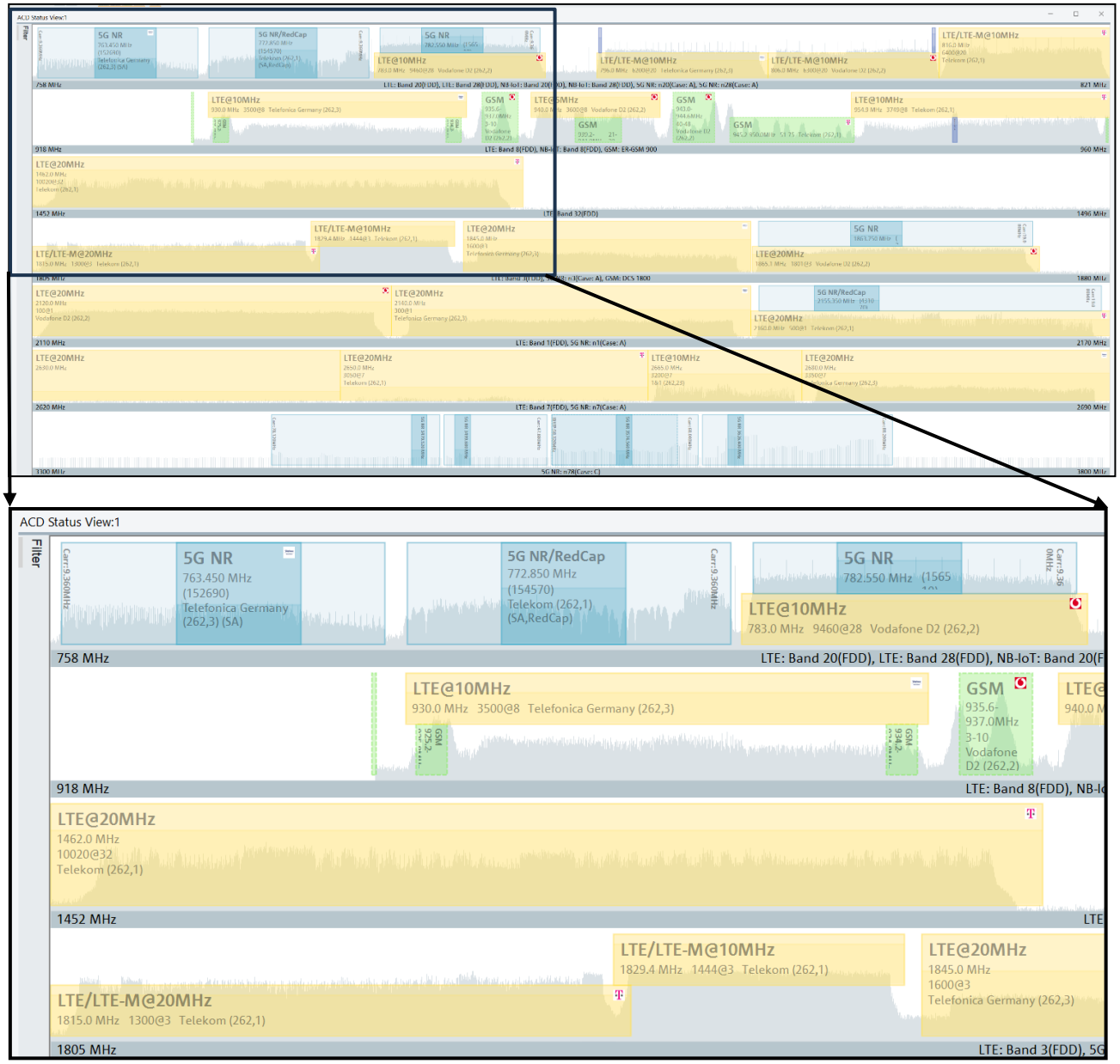
– Use of different technologies on both sides of a border;

– Signals from distant foreign networks arriving after the guard interval due to ducting effects.

In such cross-border cases, suitable monitoring systems can be configured to scan all cellular technologies and all bands (or a selection thereof) as defined for the cellular standards of interest. The relevant RF and network parameters from the serving base station as well as from neighbouring cells can be measured and displayed. Figure 6-81 shows an example of a measurement overview with signals from multiple operators and multiple technologies and multiple frequency bands.

FIGURE 6-81

Overview of identified cellular signals: Automatic Channel Detection



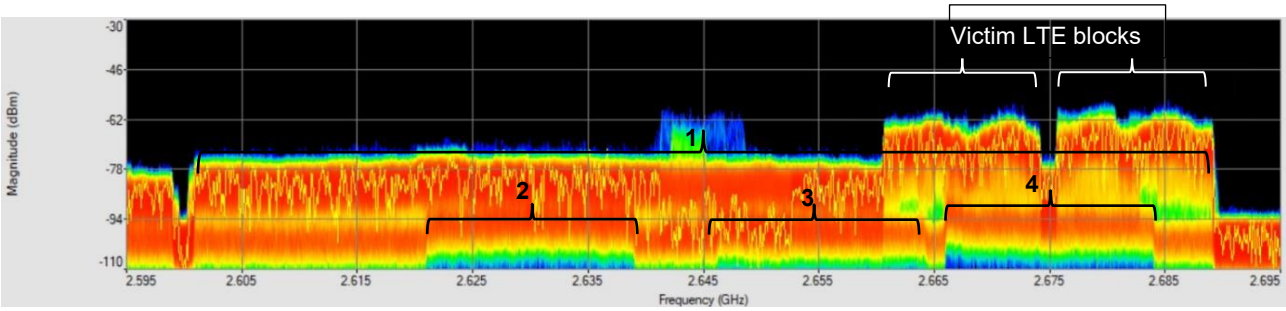
Regarding the interference measurement reports from the affected base stations, this type of interference looks like a broadband signal covering part or even all the used channel.

Common lengths of guard intervals in TDD bands are designed to cover signals from around 50 km away, which corresponds to a delay time of arrival of around 17 µs. Any signal arriving later causes interference. To detect the interference, the measurement equipment must be able to perform a time gated measurement which can be synchronized with the victim network (commonly using a GNSS time base). Therefore, the measurement instruments must be able to perform measurements as short as a few µs.

Spectrum or even persistence spectrum displays like in Fig. 6-82 are not sufficient in this case as shown in the example in Fig 6-82. The victim network in this example uses 2 LTE TDD blocks of 15 MHz bandwidth each, between 2 660 and 2 690 MHz.

FIGURE 6-82

Persistence spectrum display of a co-channel interference scenario in TDD networks



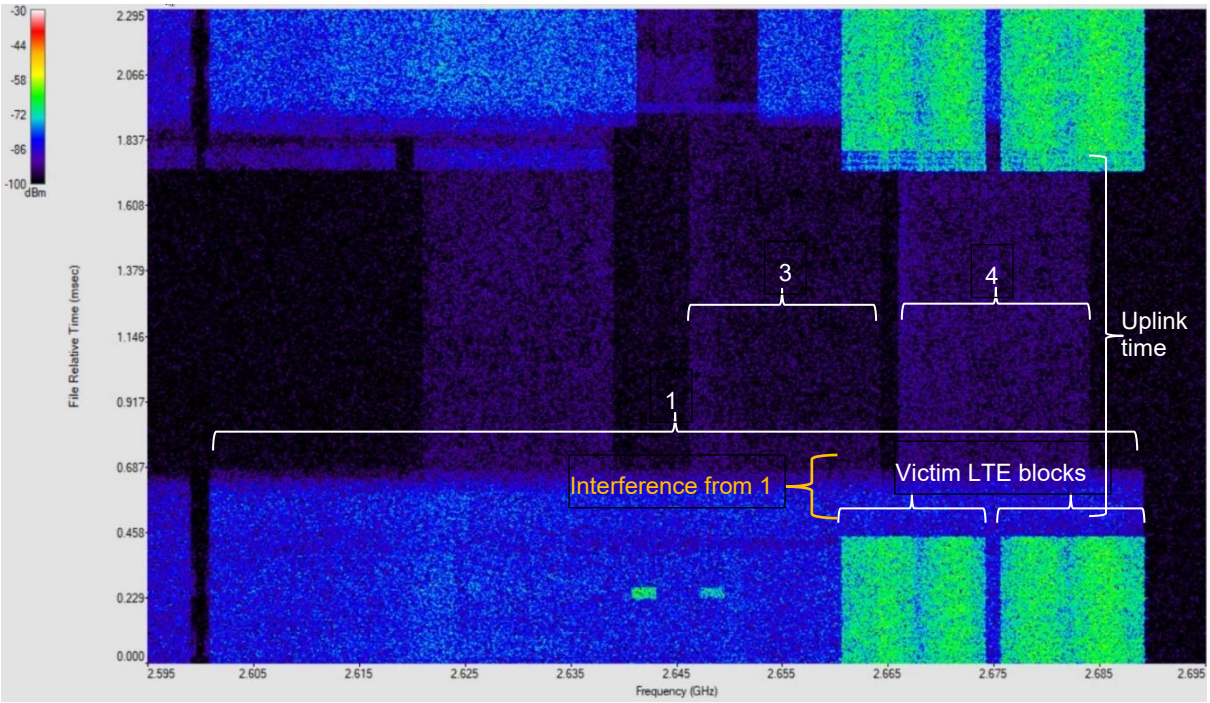
Besides the two wanted (victim) LTE blocks, the persistence spectrum shows four additional signals:

- a 5G NR signal from 2 600 to 2 690 MHz;
- a 20 MHz wide LTE signal from 2 620 to 2 640 MHz;
- a 20 MHz wide LTE signal from 2 645 to 2 665 MHz;
- a 20 MHz wide signal from 2 665 to 2 685 MHz.

Except for signal (2), the other signals are overlapping in frequency with the wanted channels and could be potential interferers. However, it cannot be seen from the persistence display whether they are also overlapping in time and present in the uplink slots of the victim systems, because only then they would actually be interferers. To investigate the time behaviour of the different signals, the measurement instrument, which is preferably a realtime analyser, must be able to produce a spectrogram with a time resolution of at least a few µs. Figure 6-83 shows the spectrogram of the situation in the previous figure around the uplink slot of the victim system.

FIGURE 6-83

High resolution spectrogram of the co-channel interference scenario in Fig. 6-81



Only in this spectrogram we can see that all three overlapping signals are actually interferers:

- The 5G NR signal (1) arrives considerably late and interferes with the first quarter of the uplink slot.
- The two LTE signals (3) and (4) are actually FDD signals and interfere with the whole uplink time.

This example shows a situation that was caused by ducting, but it may also be experienced in the border region of two adjacent countries. The 5G NR signal is probably time-synchronized with the victim network, but due to the high distance it arrives 190 µs late which means the interfering station is about 60 km away.

Theoretical solutions to this situation include decreasing the downtilt, change the main beam direction, or reduce the power of the interfering station(s). Other solutions would be to increase the guard period on both interfering and victim station(s). However, all these solutions will have a negative effect on the interfering network as it decreases its coverage.

Using different systems on both sides of the border as in the example above where TDD and FDD are mixed should generally better be solved by coordination.

Report ITU-R M.2559 contains detailed information on mitigation techniques.

6.3.8 Coverage measurements

Often, one condition in the licence for cellular networks is that a certain area or percentage of the population is covered with the service. In order to verify whether operators comply with these conditions, and also in cases of complaints from customers, Monitoring Services has to measure the coverage.

Under which conditions a location is regarded as being "covered", depends on the conditions in the respective network licence or agreements between regulator and network operators. In the simplest case, it is a technology-dependent minimum field strength, usually converted into an input level at the receiver under the assumption of an antenna gain of 0 dBi. In other cases, however, it can also be required that a certain quality of service (QoS) is provided at a covered location, e.g. a minimum data rate.

Coverage measurements of cellular systems are usually done with portable equipment or mobile measurement vehicles using dedicated equipment that is able to decode the signal from the nearest base station(s). Some of these systems are able to actively connect to the network in order to measure QoS parameters.

It is obvious that performing the coverage measurement on all locations throughout a country is neither practicable nor efficient. Instead, the following measurement approaches are common:

1) Perform a mobile measurement in certain test areas or test routes only, and extrapolate the result to the whole area or population of the country. Detailed information on the selection and calculation of the number of required test areas can be found in Annex A to Recommendation ITU-T E.806.

2) Crowd sourcing: This technique relies on data that is collected in the background of prominent apps running on smartphones and with the cooperation of many individuals who install an app which collects network measurements at user interaction. More information can be found in ECC Report 341. The results are stored on the server. After a sufficient number of random measurement results, extrapolation to the whole area or population is possible.

Both methods above result in a certain percentage of the area or population being covered with the cellular service, but they do not deliver information on the coverage of any exact location. If this is required, for example if the licence conditions contain an obligation to cover certain streets, railroads, or villages, the first method has to be applied and place the test areas exactly where required.

Detailed explanation on both methods as well as a discussion on the pros and cons of each method are contained in ECC Report 341 for 5G NR, ECC Report 256 on the example of LTE and in ECC Report 103 on the example of UMTS. As from 5G-NR, there can moreover be a difference in IDLE-mode and CONNECTED-mode coverage, in case the signalling- and data-beams have different antenna patterns. See ECC Report 341 for more information.

To measure the coverage of a cellular system independent of a specific type of user equipment, special monitoring systems such as passive network scanners are necessary that are able to continuously measure the relevant system parameters along a route.

6.3.8.1 Drive or walk test method

Positioning the test areas for this method requires information from the network operator. To optimize and plan their network, computerized planning tools based on propagation models are used that result in nationwide digital maps showing the areas that are supposed to be covered. These maps have to be requested from the operator when planning the coverage measurement.

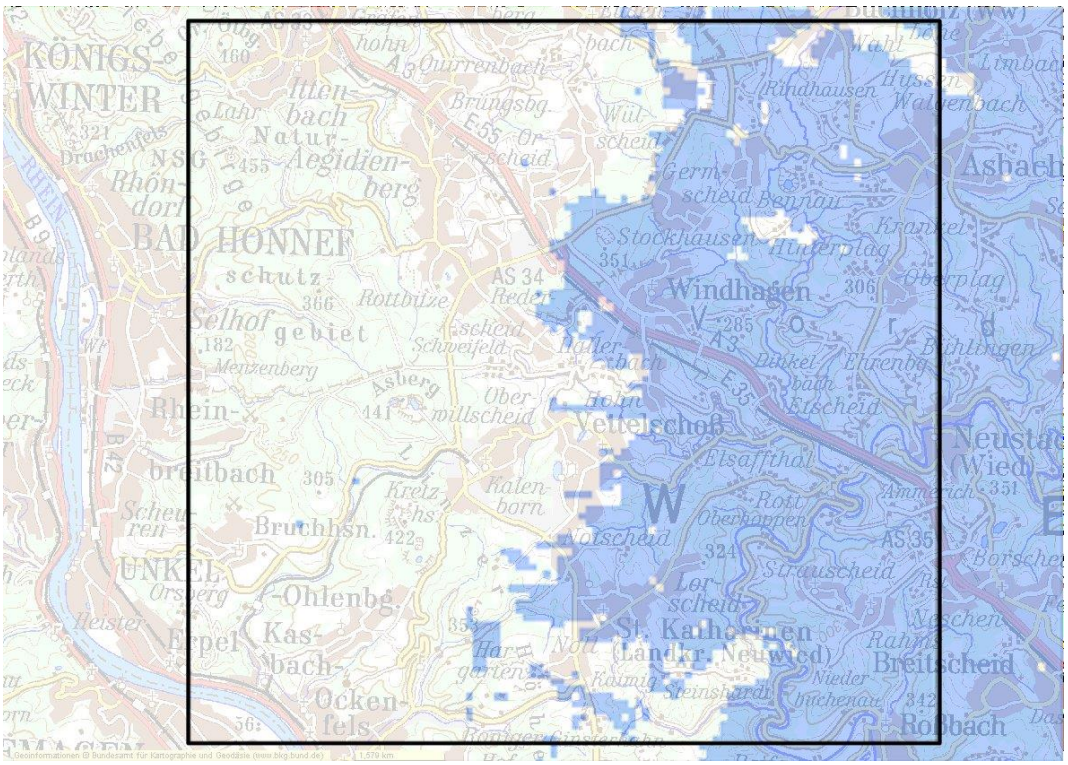
Coverage prediction maps are always based on field strengths. To verify those maps, measurements of the field strength are sufficient. However, prior to the measurement campaign it is necessary to agree on the minimum field strength value where the required network performance is assumed. This value depends on the coverage criterion defined in the licence. For example, if only access to the network is required, a lower field strength value applies compared to the requirement to get a specific minimum data rate. Further details on the drive and walk test method can be found in Recommendation ITU-R SM.1447.

If QoS is to be measured with the aim to assess the population covered, the test areas may be defined in a way that they contain areas with equal population or usage density, or equal geographical structure, such as described in Recommendation ITU-T E.806.

If the main aim is to verify predicted or calculated coverage, arbitrary, but not overlapping rectangular test areas of about 10 × 10 km size may be placed over the coverage maps in a way that a certain percentage lies in areas predicted as covered, and the rest in adjacent areas where the prediction has no coverage. Ideally, 50% of the test area should be in a predicted coverage area. Figure 6-84 shows an example of a test area. The blue shaded part shows the area where the operator predicted coverage.

FIGURE 6-84

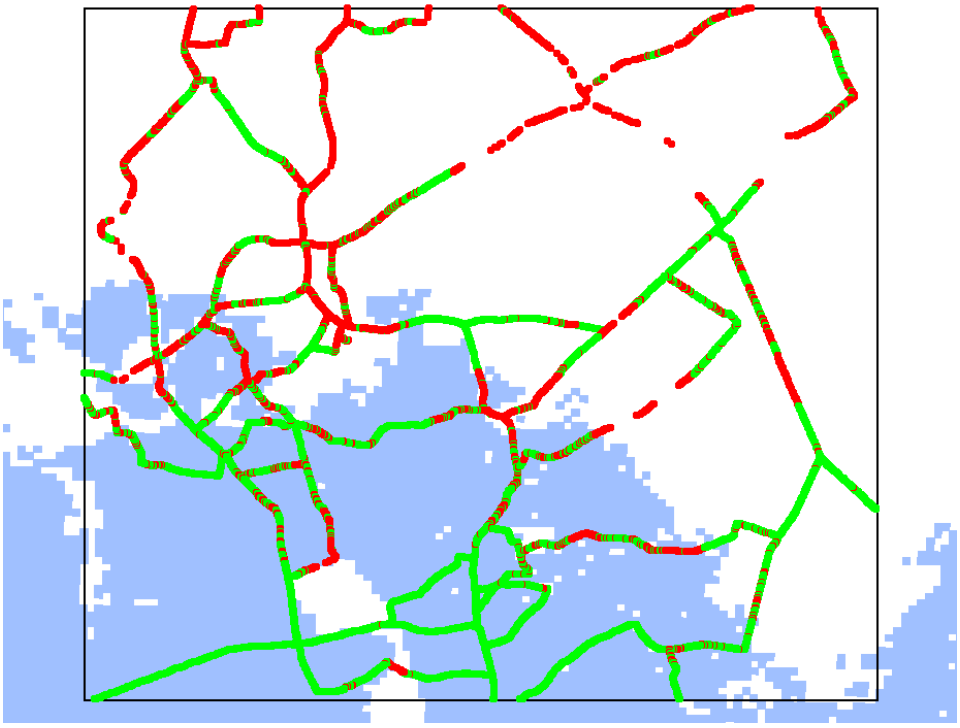
Example of a test area to measure coverage of a cellular network (Source: ECC Report 256)



Then, with the required equipment, measurements are performed while driving every road inside the test area. The result can be displayed on a map containing the predicted coverage and the test result as coloured dots or lines (e.g. green for covered and red for not covered). Figure 6-85 shows an example.

FIGURE 6-85

Example of a coverage measurement result in a test area (Source: ECC Report 256)



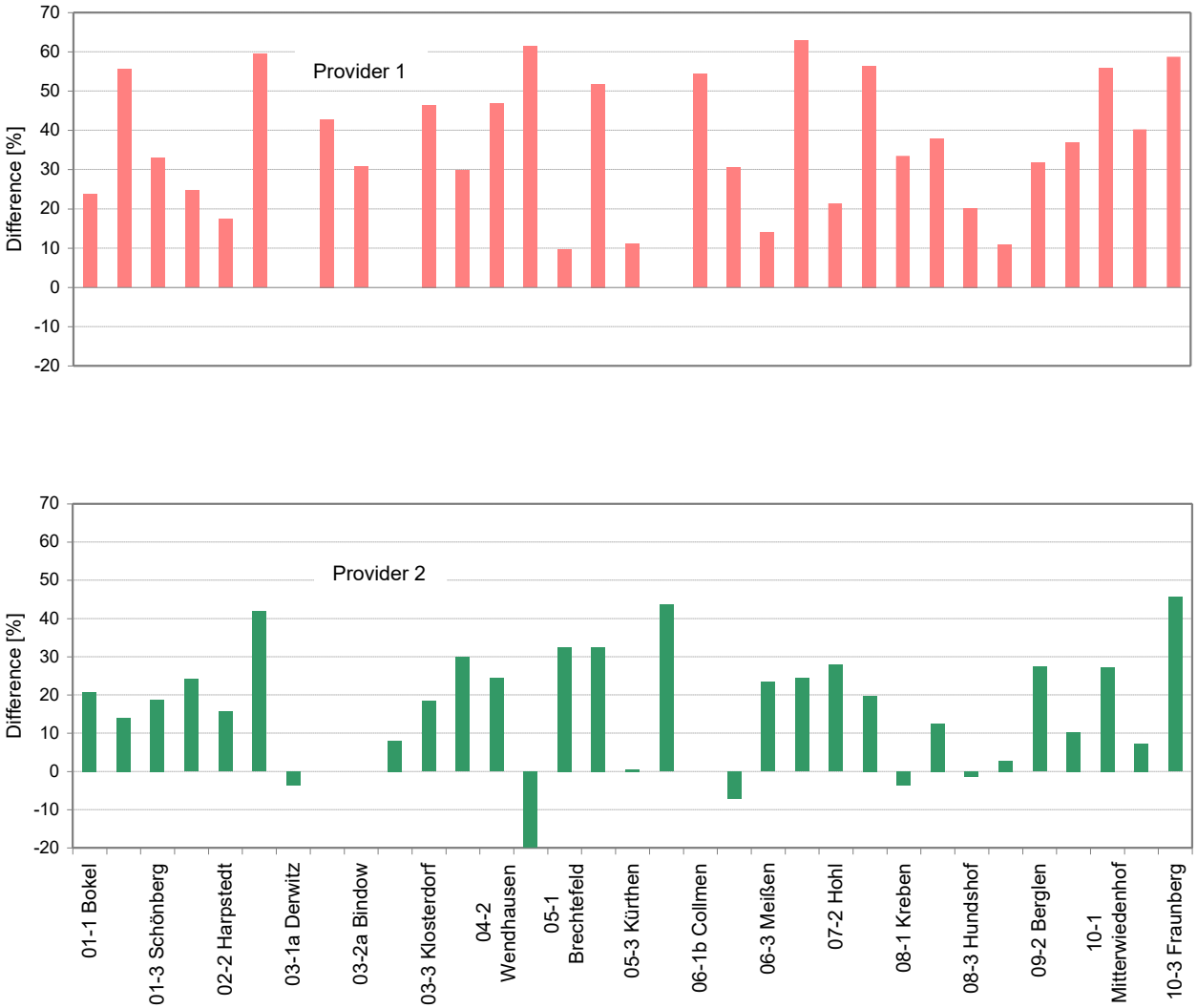
Then, the percentage of measurements exceeding the coverage criterion is compared to the percentage inside the test area where the operator predicted coverage. If the measured percentage of covered locations are equal or even exceed the percentage of predicted coverage inside the test area, it can be assumed that the parameters which were used by the operator to calculate his coverage were realistic (or even pessimistic).

This evaluation is repeated for all test areas and an average is calculated. It is assumed that if the coverage prediction in the test areas was realistic, this result can be applied to the whole country.

The predicted total area for the whole network from the operator can then be used to check whether that coverage meets the minimum requirements in the licence, or whether the parameters entered for the coverage predictions were realistic. The result can be expressed in graphical form like in Fig. 6-86.

FIGURE 6-86

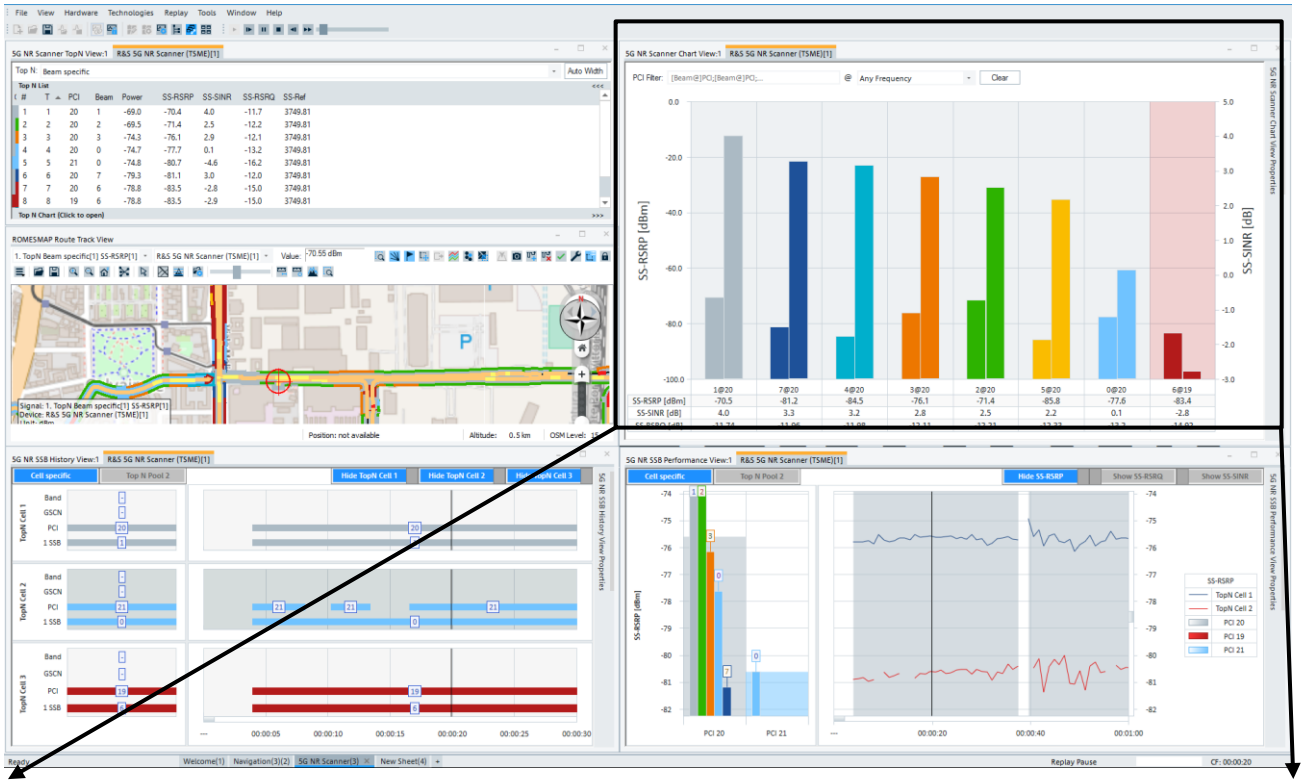
Comparison between prediction and measurement inside reference areas for each test area. Positive bar means that more area is covered than predicted, negative bars indicate that actual coverage area is smaller than predicted

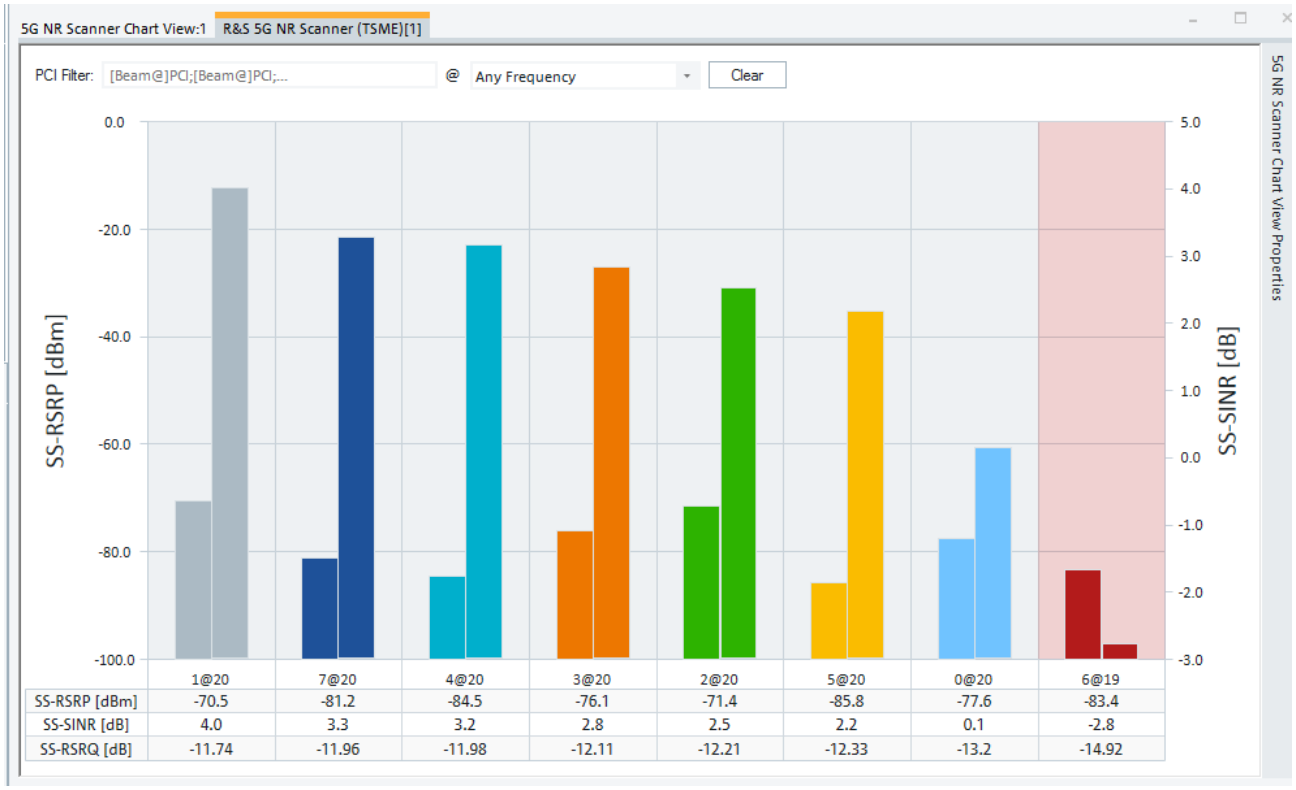


In addition to field strength values, coverage measurements can be extended to include many other system parameters. In IMT networks, for instance, power level, quality, cell identification, spreading code, and other parameters can be monitored. An example of 5G NR signals (gNodeB always-on SSB signals) with various cell- and beam-specific measurements is shown in Fig. 6-87.

FIGURE 6-87

5G NR signal measurements – cell/PCI and SSB beam specific





6.3.8.2 Crowd sourcing method

Especially in cellular networks where often the overall network performance is to be assessed, crowd sourcing is often an effective method, requiring little manpower from the monitoring service.

The regulator provides a smartphone application which can usually be downloaded for free for the user's device. After installation by the user the application gathers information concerning the network parameters and documents the geographical position of the measurement.

A basic indicator for the received signal strength is the RSSI value. The mobile phone uses this indicator to find an appropriate channel. Thus, in the case that the signal strength falls below a certain threshold the RSSI value is used to switch to a more optimal channel. By referencing the RSSI value to a device dependent scaling factor this value can even be expressed in dBm. On the one hand are mobiles non-calibrated devices, thus the given dBm value cannot be compared to qualified measurements carried out by a regulator. On the other hand, the measurement via mobiles provides elementary information about the network coverage, but these are only related to the specific points where the measurements were done.

Many applications on the market also make use of the GPS data provided by the mobile phone. With this information network coverage heat maps can be created, that provide information about the coverage where the measurements were done.

One major issue with crowd sourcing is that usually no information about the receiving scenario where the measurement was taken is available. This may lead to completely different results of two measurements taken at the same location. If, for example, users were on top of a roof, they may have got an excellent reception with a high data rate. If, on the other hand, they were in the basement of the same building, reception may be poor or not even possible.

A statistically relevant picture of the overall network coverage with crowd sourcing can therefore only be gained by averaging a very high number of measurements.

6.3.8.3 Quality of service (QoS) and Quality of Experience (QoE) measurements

In addition to a signal level coverage requirement, spectrum license obligations increasingly require also a certain level of service (Quality of Service, Quality of Experience).

Especially in cellular radio systems with their dense network of base stations, intra- or extra-network interference may result in the degradation of certain parameters attached to the so-called quality of service (QoS). These parameters can only be measured with specialized monitoring equipment that is tailored to the relevant cellular system. The following list of parameters affecting the actual usability of a cellular network at a given location is not exhaustive:

– Signal-to-noise ratio (*S*/*N*) and signal-to-interference plus noise ratio (SINR).

– Bit error rate/packet error rate/symbol error rate.

– Time delay of reflected signals due to multipath conditions/channel impulse response.

– Handover conditions.

As QoS measurements deal with purely technical parameters, those QoS results are often difficult to translate into actual network performance as experienced by the user. Hence it may also be helpful to carry out Quality of Experience (QoE) measurements. A typical QoE measurement consists of performing a typical user scenario, like file transfer or video call or other apps using smartphones (LTE and 5G), and observing the different relevant quality parameters, or Key Performance Indicators (KPIs) such as:

- Average download and upload data rate;
- Audio and video quality (MOS);
- Number of interruptions of a video stream;
- Time for completing an action within an app (e.g. social media, web browsing).

Those KPIs can also be blended into a single Network Performance Score (NPS) as explained in ETSI TR 103 559 (*Best practices for robust network QoS benchmark testing and scoring*) in order to compare the quality and performance of different mobile networks in a transparent and harmonized way.

Since the values of QoS and QoE parameters are dependent on the specific location, these monitoring systems are best fitted in measurement vehicles for drive tests or in backpack solutions for walk tests. Figure 6-88 shows an example of such a system together with some sample measurement evaluation displays that are possible.

FIGURE 6-88

Example of a measurement system for cellular radio networks

6.3.9 References

ITU Radio Regulations

Resolution ITU-R 56-3 – *Naming for International Mobile Telecommunications*

Handbook on International Mobile Telecommunications (IMT)

EU/CNC 6G Summit 6-9 June 2023, Sweden

ETSI TR 103 559 Speech and multimedia Transmission Quality (STQ); Best practices for robust network QoS benchmark testing and scoring

ITU-T Recommendations

Recommendation ITU-T E.806 – *Measurement campaigns, monitoring systems and sampling methodologies to monitor the quality of service in mobile networks*

ITU-R Recommendations

Recommendation ITU-R SM.1447 – *Monitoring of the radio coverage of land mobile networks to verify compliance with a given licence*

ITU-R Reports

Report ITU-R M.2559 – *Mitigation of interference due to tropospheric ducting effect within an International Mobile Telecommunications network*

ECC Reports

ECC Report 103 UMTS coverage measurements

ECC Report 256 LTE coverage measurements

ECC Report 341 Coverage availability and performance aspects for 5G NR

ECC Report 345 In-band measurement methodologies for 5G AAS base stations in the field

6.3.10 Abbreviations/Glossary

3GPP	3rd Generation Partnership Project
3G	3rd Generation of cellular systems
4G	4th Generation of cellular systems
5G	5th Generation of mobile communications
ARIB	Association of Radio Industries and Businesses
BS	Base station
BCCH	Broadcast control channel
C0	A GSM BS uses at least one RF frequency, called C0
CDMA	Code division multiple access
DECT	Digital enhanced cordless telecommunications
EDGE	Enhanced data rate for GSM Evolution
EIA	Electronic Industries Association
FDD	Frequency division duplex
FDMA	Frequency division multiple access
FR	Frequency range
GPS	Global positioning system
IEC	International Electrotechnical Commission
LTE	Long term evolution
NR	New Radio
RMS	Root mean square
RTWP	Received total wide band power
SSB	Synchronization and signalling block
OFDMA	Orthogonal frequency division multiple access

QoS	Quality of service
TDD	Time division duplex
TDMA	Time division multiple access
TIA	Telecommunications Industry Association
UE	User equipment
UMTS	Universal Mobile Telecommunications System

6.4 Microwave links and satellite uplinks

6.4.1 General introduction

Except for a limited number of terrestrial radio-relay or microwave systems below 1 GHz, it is generally assumed that microwave links operate above this frequency. This section deals with satellite uplinks, whose detection and control is different, compared to classical radio links.

The technology of microwave radio systems is founded on the possibilities offered by frequencies from 1 to 100 GHz, to which correspond certain short wavelengths called microwaves (30 cm > λ > 3 mm). These two aspects provide both wide base-bands and directive radiations, particularly suitable for transmitting large quantities of signals or data from point to point. Three types of propagation are used:

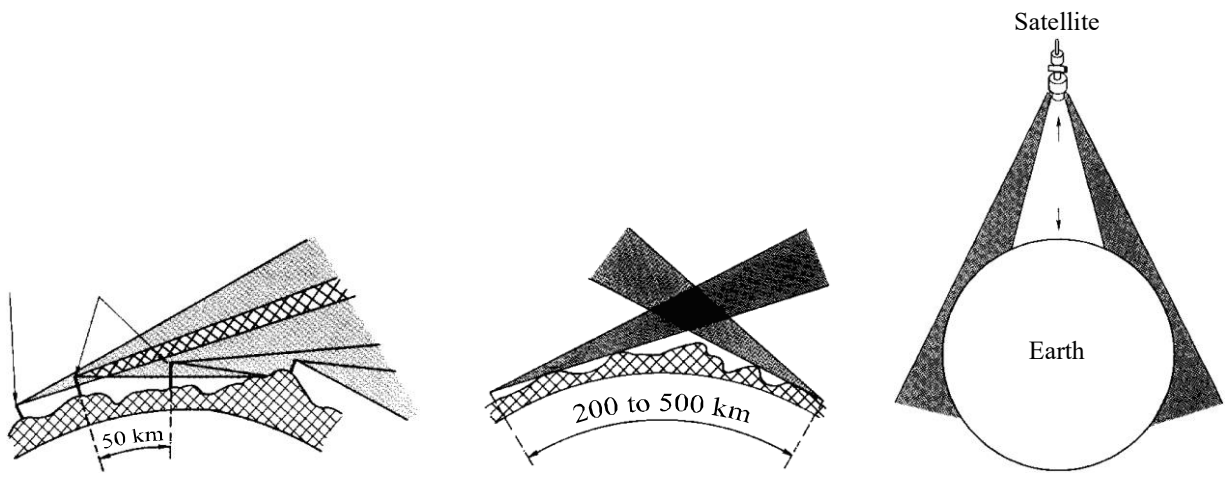
– Line of Sight (LoS): to avoid the problem of the Earth's roundness, repeaters, receivers and transmitters are installed at approximately every 50 km. One link or a series of radio hops is called a radio link (see Fig. 6-89a). The propagation is fairly stable.

– Troposcatter: in order to reach a radio hop extremity which would be beyond the optical horizon (see Fig. 6-89b). The reception is weak and fluctuating; see Recommendation ITU-R F.302.

LoS with a satellite: placed in a Geostationary Satellite Orbit (GSO) at an altitude of circa 36 000 km (see Fig. 6-89c) and which contains an active repeater and antennas oriented toward the Earth.

FIGURE 6-89

Types of propagation



a) Line of sight b) Forward scatter c) Satellite communication

Spectrum-5.4-01

6.4.2 Use of microwave links

Microwave links are typically point-to-point (P-P) (often with multiple links or chains of repeaters) with point-to-multipoint systems using latest technology. The distance between repeaters changes depending on used propagation mechanism and frequency from several km (LoS) to several ten thousands km (satellite). The use of digital techniques to regenerate the signal, usually having a low signal to-noise ratio at the far end of a link, allows increasing this distance.

The directivity of the transmitted signal also allows extension. Some systems operate up to frequencies as high as EHF, e.g. till 300 GHz where links of over several hundred meters; see Report ITU-R F.2416.

Concerning troposcatter communication, it employs the ability of the troposphere, acting as reflective medium, for providing communication between two long distance points, of several hundred km. Table 6-20 provides information on comparison between the two types of propagation LoS and troposcatter.

TABLE 6-20

Comparison of LoS microwave versus troposcatter

Item	LoS	Troposcatter
Voice Frequency (VF) channel	Up to 1 800/2 700 per carrier	Up to 240 per carrier
Bit rate	90 Mbit/s or more per carrier	2 400 bit/s to 4 Mbit/s per carrier
Path length (km)	1.6-80	80-800
Transmit power (W)	0.1-10	100-50 000
Receiver noise figure (dB)	4-12	Less than 4
Diversity	None or dual	Dual or quadruple
Antenna aperture size (m)	0.3-4	1.5-40

The third type of propagation used in microwave communication is the transmission and reception of a telecommunication link via satellite.

The general configuration of an earth station is not substantially different from that of a radio-relay terminal, but the very large free-space attenuation (about 200 dB) undergone by the carrier radio waves on their path between the station and satellite (approximately 36 000 km) usually requires the main sub-systems of an earth station to have a much higher performance level than those of a radio-relay terminal.

The spectrum beyond 275 GHz can support bit rate capacities on the road toward 100 Gbit/s; see Report ITU-R F.2416. Most microwave links are digital.

Channel Arrangements (CAs) and Blocks of the Fixed Point-to-Point and Point-to-Multipoint are detailed in the following Table[4]; the rows are assorted by frequency.

[4] Mazar (2016). Section 2.4 'Fixed Point-to-Point and Point-to-Multipoint' Table 2.22 'Channel Arrangements (CAs) and Blocks' Radio Spectrum Management: Policies, Regulations and Techniques.

TABLE 6-21

Channel Arrangements (CAs) and Blocks at ITU-R F-series Recommendations[5]

Nº	RF band	Rec. ITU-R	Nº	RF band	Rec. ITU-R
1	406.1-450 MHz	F.1567	*15*	Blocks at 10.15-10.3/10.5-10.65 GHz	F.1568
2	1 350-1 530 MHz	F.1242	*16*	10.7-11.7 GHz	F.387
3	1 350-2 690 MHz	F.701	*17*	14.4-15.35 GHz	F.636
4	1 900-2 300 MHz	F.1098	*18*	17.7-19.7 GHz	F.637
5	2 290-2 670 MHz	F.1243	*19*	21.2-23.6 GHz	F.748
6	2 and 4 GHz	F.382	*20*	25, 26, 28 GHz	F.1520
7	Blocks at 3 400-3 800 MHz	F.1488	*21*	31.8-33.4 GHz	F.749
8	3 400-4 200 MHz	F.635	*22*	36-40.5 GHz	F.2005
9	4 400-5 000 MHz	F.1099	*23*	CA and blocks at 40.5-43.5 GHz	F.1496
10	5 925-6 425 MHz	F.383	*24*	51.4-52.6 GHz	F.2006
11	6 425-7 125 MHz	F.384	*25*	CA and blocks at 71-76 and 81-86 GHz	F.2006
12	7 110-7 900 MHz	F.385	*26*	92-95 GHz	F.2004
13	7 725-8 500 MHz	F.386	*27*	111.8-114.25 GHz	F.2173
14	10.0-10.68 GHz	F.747	*28*	167-174.8 GHz	F.2172

6.4.2.1 Digital links

Digital links display only a band of spectral occupancy visually similar to filtered white noise. It is not immediately evident from RF spectra whether any of the separate base-band channels are occupied or not. It is necessary to discuss the construction of these signals before any analysis is considered.

The source will typically be a single multiplexed digital signal as described by Recommendation ITU-T G.703. This describes the data and framing protocol of line digital links.

Since the transmitter has no control over the nature of the digital signal, it is exclusively ordered by a pseudo-random digital sequence generated within the system. The reason for this is to avoid situations of a no-data microwave signal (spectral dispersion) and, in some cases, to provide sufficient digital transitions for clock recovery. There is no global specification for this randomizing sequence that differs with equipment type and manufacturer.

Similarly, digital modulation methods are equally varied, but may be consistent in any one band, depending on national spectrum management policy. QPSK or differential QPSK (DQPSK) is common but various quadrature amplitude modulation (QAM) schemes are used representing various ways of enhancing spectral efficiency and system design.

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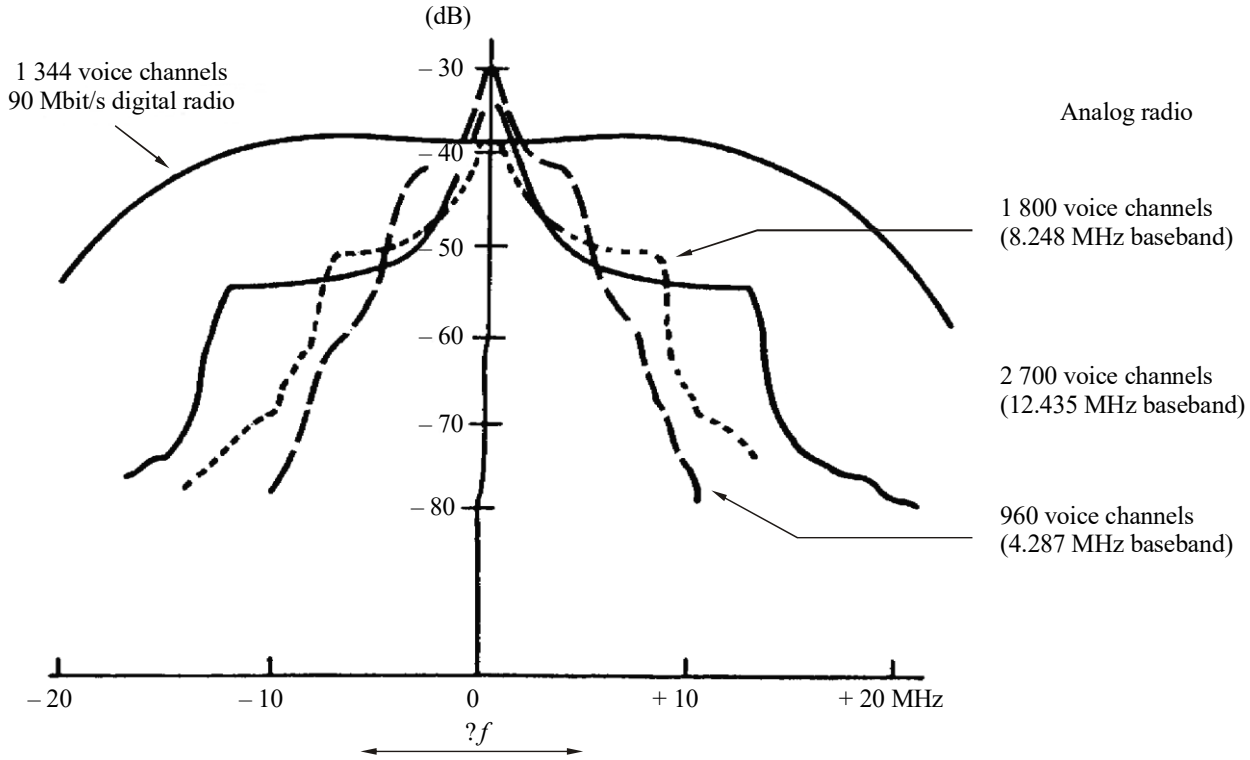
5 Table 6-21 details Channel Arrangements and Blocks of the Fixed Point-to-Point and Point-to-Multipoint; the rows are assorted by frequency. The eight Recommendations are not repeated at this section.

6.4.2.2 Output spectrum

The analogue mask of the point-to-point P-P radio differs from the digital P-P, as shown in Fig. 6-90.

FIGURE 6-90

Comparison of analogue and digital RF masks



Spectrum-5.4-02

Notice how the digital P-P mask almost completely fills the band, whereas the analogue mask has the peak at the carrier frequency and sidebands gradually decreasing in amplitude at frequencies away from the carrier. It is this characteristic which makes the analogue P-P vulnerable to interference by digital P-P. If the frequency band of a digital P-P operates too close to that of an analogue, the large amplitude at the edges of the band of the digital P-P can swamp the low-amplitude sidebands of the analogue, causing interference so severe that the analogue P-P fails. This point stresses the need for adequate Intermediate Frequency (IF) and RF filtering of microwave radio signals whose bands are operating very close to each other on the same route.

6.4.2.3 Multiplexing in microwave radio systems

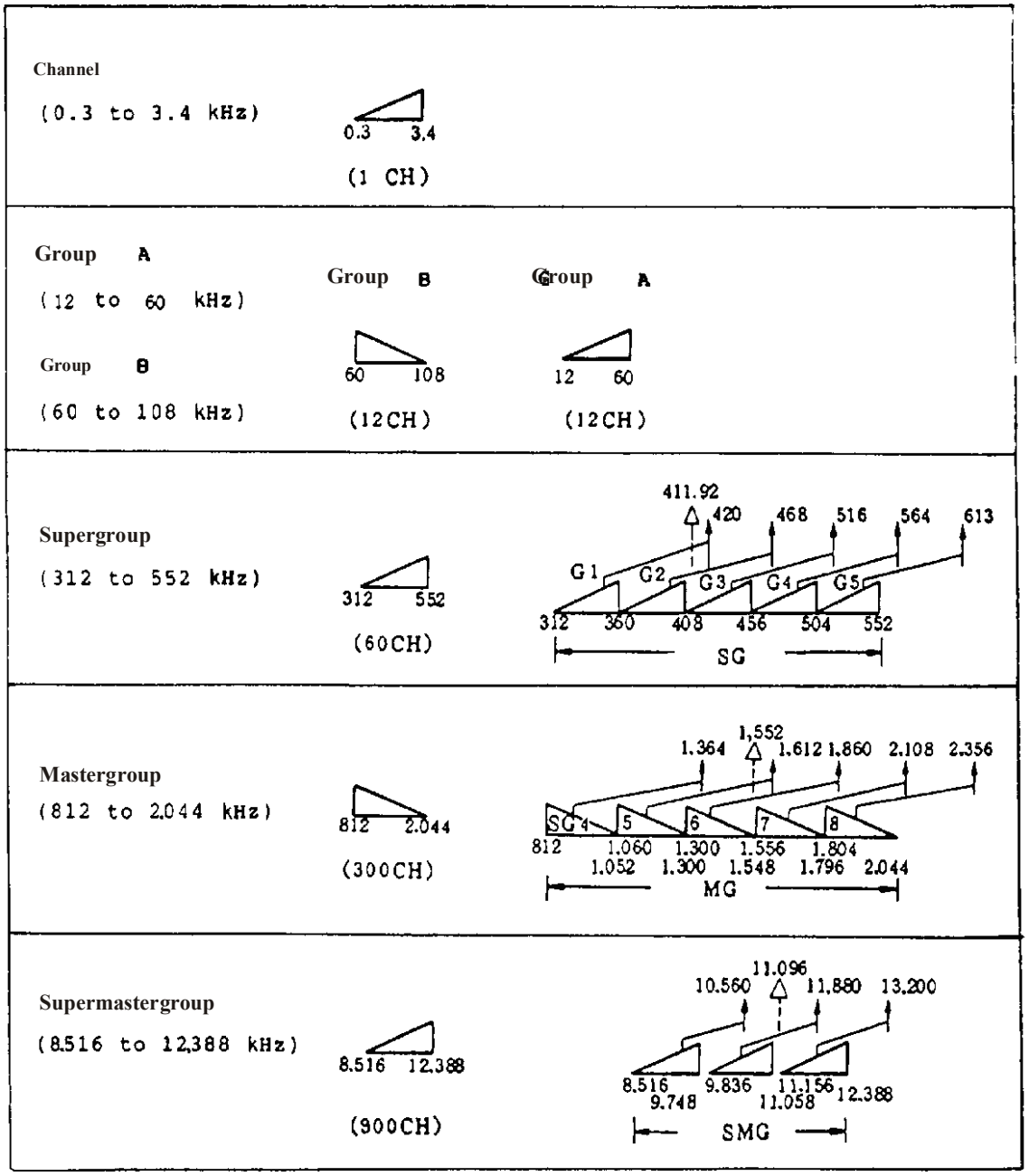
Multiplexing is the sending of a number of separate signals together, over the same carrier, simultaneously and without interference.

6.4.2.3.1 Frequency division multiplex

Frequency Division Multiplex (FDM) (see Fig. 6-91) combines continuous (or analogue) signals. It may be thought of as an outgrowth of independent-sideband transmission, on a much-enlarged scale. As will be seen, 12 or 16 channels are combined into a group, 5 groups into a super group, and so on, using frequencies and arrangements that are standard on a worldwide scale. Each group, super group or larger aggregate is then sent as a whole unit on one microwave link, cable or other broadband system.

FIGURE 6-91

FDM frequency grouping



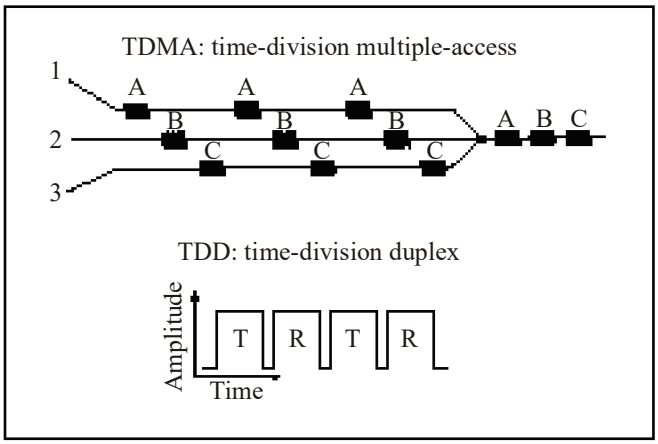
Spectrum-5.4-03

6.4.2.3.2 Time division multiplex

Time Division Multiplex (TDM) (see Fig. 6-92) is a method of interleaving, in the time domain, pulses belonging to different transmissions. Using the fact that pulses are generally narrow, and separation between successive pulses is rather wide. Therefore, it is possible, provided the two ends of a link are synchronized, to use the wide spaces for pulses belonging to other transmissions.

FIGURE 6-92

Multiplexing – Time



Spectrum-5.4-04

6.4.2.4 Monitoring operation

The use of wide band microwave transmissions increases (fixed wireless access services for example). Interference between these systems has to be taken into account by membership, to reduce interference by:

– investigation and elimination of harmful interference caused by microwave or other systems;

– compliance with technical parameters;

– detection of illegal transmissions.

It is difficult to detect (in order to enforce regulations) illegal transmissions of microwave systems, as these systems use directional antennas. Thus, monitoring of these transmissions is done by mobile units, because of the reduced and narrowed geographical area covered by the transmitted signal at levels that can be received. Normally, to measure such a system, the monitoring antenna has to be in the main-beam of the microwave transmitting antenna, or otherwise closely coupled to the transmitter or feed line. A reliable method to achieve this is to locate the signal with a coarse adjustment of the antenna heading in both azimuth and elevation. Using the spectrum analyser to locate the peak signal, the span of the analyser can be reduced to zero and the sweep time extended to around 60 s. (This sweep time is not critical, but provides a visual trace to refer to.) Adjusting the antenna in one axis at a time the peak value will be found. It is important to look beyond the first peak in order to check alignment on the main lobe. Side lobes will be seen on either side of the main lobe. Once the peak value has been found the procedure is repeated for the other axis. If using a receiver, it will be necessary to mentally track its signal strength to identify the peak values. Once the antenna direction has been optimized the required span, bandwidth, etc., can be re-established on the spectrum analyser with the appropriate detector modes set.

6.4.3 General techniques for measurement

In general, basic parameters to be measured are:

– carrier frequency;

– field strength or power flux-density (pfd);

– occupied bandwidth;

– deviation from assigned frequency;

– polarization;

– class of emission and modulation;

– identification of signal source.

The capability to perform additional measurements and observations beyond those indicated above is desirable for purpose of interference modelling. The addition of this capability increases the effectiveness of the monitoring facility as a spectrum management tool. The additional parameters that may be measured or observed depend on the type of emission as listed in Table 6-22.

TABLE 6-22

Parameters of emissions for additional measurements

Emission	Parameter
FDM-FM	Frequency and amplitude of baseband signals
	Number of voice or other channels
	Peak deviation of the carrier
	Frequency and amplitude of the energy dispersal signal
TV-FM	Frequency and amplitude of baseband signals
	Peak deviation of the carrier
	Frequency and amplitude of the energy dispersal signal
	Pre-emphasis characteristics utilised
SCPC-FM SCPC: single channel per carrier	Peak deviation of carriers
	Highest modulating frequency
	Carrier spacing
	Number of carriers per transponder
	Channel occupied bandwidth
	Relative power per carrier
Digital (PSK, FSK, SCPC, etc.)	Bit rate
	Number of phases
	Number of amplitude levels
	Number of carriers per transponder
	Carrier spacing
	Occupied bandwidth of channels
	Relative power per carrier

This may be accomplished using:

– direct interception system, or

– interception system using RF mixers.

6.4.3.1 Direct interception system

In this method the measured signal or survey band is applied directly to the spectrum analyser or receiver via the antenna, filter and feeder, no signal conversion takes place. This system has the advantages of being simple to configure and calibrate, it gives a low set-up time and allows easy measurement observations (see Fig. 6-93).

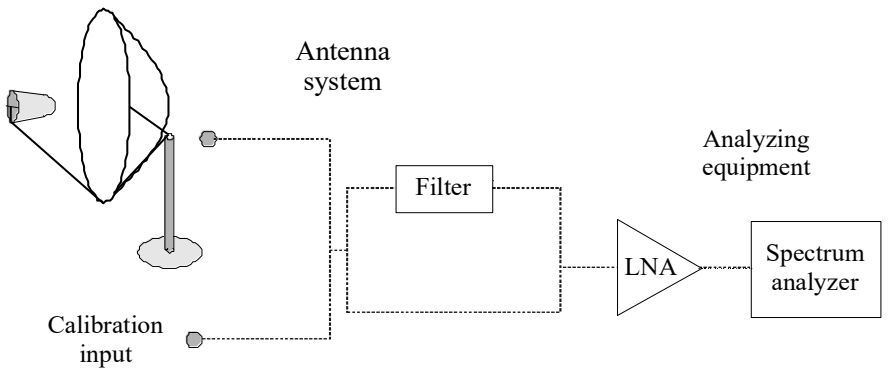
Filter could be inserted in order to reduce interfering inter-modulation products and Low Noise Amplifier (LNA) typically could be also inserted to improve the gain and noise characteristics of the measurement system. These two added elements provide an appropriate configuration to measure low level signals in the presence of adjacent emissions.

In this method, the limitation in the measurement frequency range is essentially due to the limitation of the analysing equipment (ranging up to about 85 GHz with currently available technology).

The disadvantages are that feeder losses at frequencies above 10 GHz can be considerable and detrimental to the sensitivity of the measurement system. It is essential that feeders used in this type of system are of the highest quality and that both the RF characteristics and physical condition of the cable are checked regularly. In most circumstances where measurements above 10 GHz are required the feeder length will need to be less than 1 m in length.

FIGURE 6-93

Direct interception system



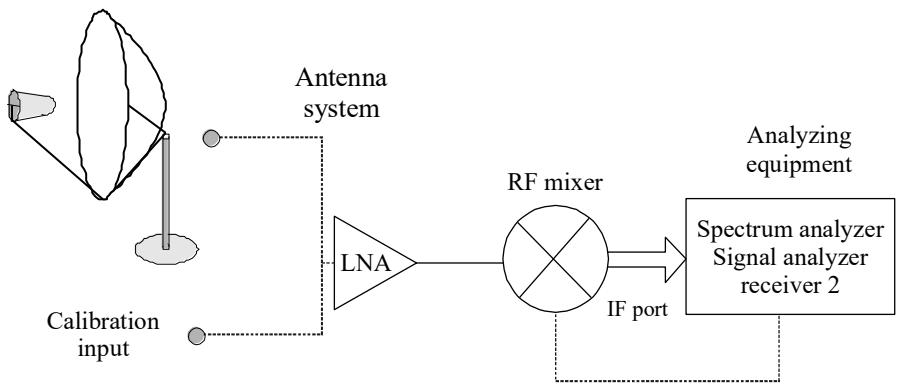
Spectrum-5.4-05

6.4.3.2 Interception system using RF mixers

In this method the measured signal or survey band is applied directly to a mixer or down converter via the antenna, filter and feeder. Signal conversion takes place and is then applied to the spectrum analyser or receiver at a lower frequency (see Fig. 6-94).

FIGURE 6-94

Interception system using RF mixers



Spectrum-5.4-06

LNA typically inserted to improve the gain and noise characteristics of the measurement system.

RF mixer extends the frequency range of analysing equipment. Two concepts are available, via single diode and double diode mixers. Due to their design, double diode mixers feature flat frequency response and require no additional biasing which makes them especially suitable for automated measurements.

In this method, the frequency range that can be covered is higher (e.g. from 18 GHz to 325 GHz) than with the direct interception monitoring method, depending on characteristics of the RF mixer, LNA, and monitoring antenna system.

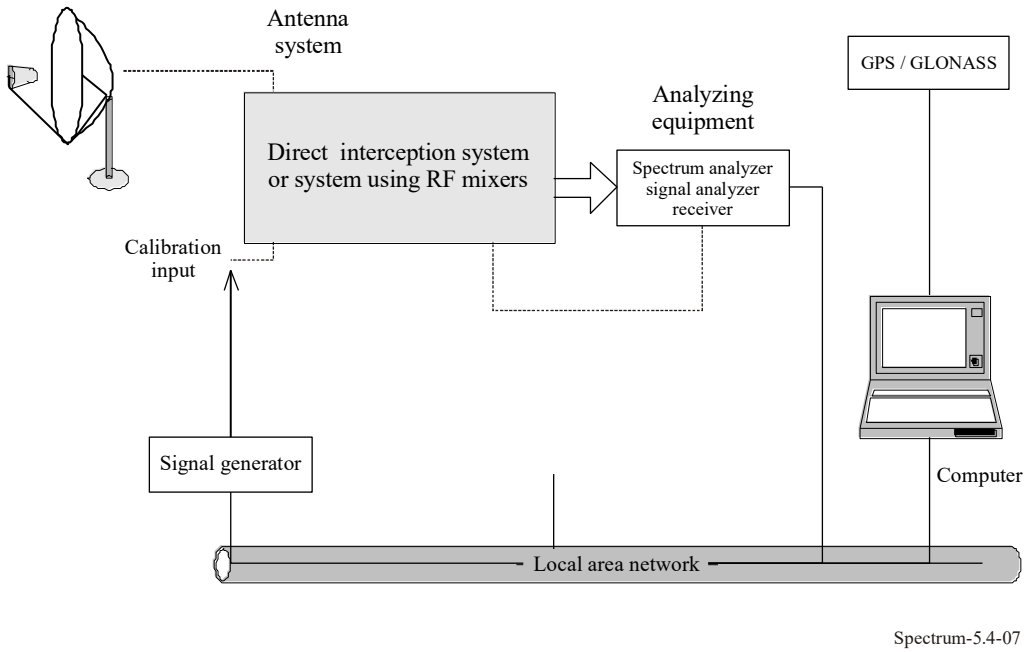
The disadvantages of this system are lower measurement system sensitivity due to conversion losses and high mixer noise figures, calibration uncertainties due to mixer drift and band flatness characteristics, inter-modulation problems, possible interference from high power systems operating on or near the down conversion frequency.

6.4.4 Equipment for monitoring vehicles

A block diagram of a microwave monitoring unit is shown in Fig. 6-95.

FIGURE 6-95

Microwave monitoring unit



6.4.4.1 Antenna system

The antenna type chosen will depend on the measurement to be carried out. Certain antenna types will have characteristics more suitable for a particular measurement task. For instance, a Horn antenna would be best suited to a polar survey to determine signals present in the survey band 360° around the measurement location, whereas a dish antenna would be better suited for direction finding a single source signal.

Horn antennas tend to be more robust and lighter weight than dish antennas and are normally easier to deploy in a transportable measurement scenario. They are also more stable in the windy conditions normally associated with elevated measurement locations. The tradeoff between the Horn antenna and Dish antenna is that Horn antennas have normally lower antenna gains, compared with Dish type antennas. Antenna physical stability (as affected by wind) is important at higher frequencies where antenna beam-widths are small.

Following these general considerations, recommendation below, according to the frequency range can be introduced.

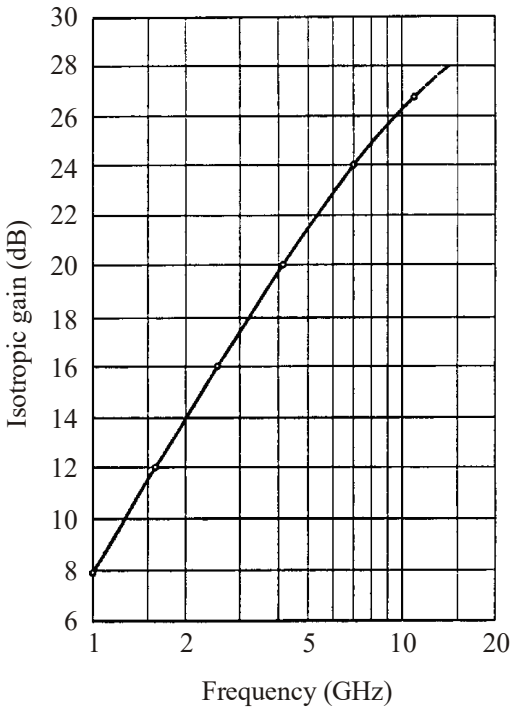
6.4.4.1.1 Frequency range from 1 to 18/26 GHz

A broadband parabolic antenna with a reflector diameter of about 90 cm or so, or a log-periodic antenna, along with an integrated preamplifier and a polarization-switching network for the feedpoint, is needed. Polarization should be selectable from X linear, Y linear, left-hand or right-hand circular.

In the vehicle, the following elements could be included YIG (Yttrium Iron Garnet) filter with a 3 dB bandwidth of 35 MHz or wider and frequency tuning from 1 to 18 GHz, and LNA with a gain of typically 40 dB. The typical gain of a 1 to 20 GHz antenna, of the type mentioned above, is shown in Fig. 6-96.

FIGURE 6-96

Typical gain of a calibrated directional log-periodic antenna with a 60 cm diameter reflector, as a function of the frequency



Spectrum-5.4-08

6.4.4.1.2 Frequency ranges 18-26 GHz and 26-40 GHz

A standard gain horn (with a reflector antenna diameter of about 1/3 m) can be used. The antenna units for the 18-26 GHz and 26-40 GHz frequency ranges could form one unit together with a horn. In the vehicle, the following elements could be included: LNA with a gain of typically 30 dB, and down converter.

6.4.4.2 Analysing equipment

Two main cases have to be considered, depending on the type of interception:

– Direct interception system:

  Traditional receivers tuning up to 3 GHz may be used with various filters and detectors, e.g. SSB, ISB, covering a range down to 12 kHz to demodulate individual audio channels. Spectrum analysers are currently available up to at least 40 GHz.

– An interception system using RF mixers:

  All available monitoring equipment (traditional spectrum/signal analyser or receiver) covering the IF band can be used. The IF output ports of the system should be amplitude matched and phase locked with the RF subsystem, thereby enabling an accurate analysis of the RF signal at the intermediate, down-converted frequency.

The following devices may be connected to the IF output port:

– Pulse analyser: for the accurate measurement of radar pulses (up to 1 ns resolution).

– Digital oscilloscope: 500 MHz oscilloscope for the analysis of repetitive signals.

– Time and frequency interval analyser: real time analyser capable of 250 Msamples/s and having a bandwidth on the order of 110 MHz.

For the analysis of modulated signals, a vector signal analyser or FFT spectrum analyser can be used to provide precise demodulation (AM, FM, PM, digital), narrow-band spectrum measurements (300 Hz-3 MHz) and measurements with a high frequency resolution (< 0.001 Hz) and accuracy (< ±0.1 ppm).

6.4.4.3 Calibration equipment

There are several ways that a measurement system can be calibrated or confidence checked before undertaking measurements.

a) Beacon method

The procedure for this calibration method is to site a temporary source operating on a frequency as close to the RF signal or in the band being investigated (taking into account other users and the interference potential to the licensed users).

The source and measurement antennas will need to be precisely aimed by use of positioners to achieve accurate calibration. An accurate distance measurement between the beacon and measuring antennas needs free space path loss propagation-conditions between antennas, to enable the calibration-frequency calculations. A calibrated signal divider, signal generator and power meter will be required to drive the beacon antenna.

In this method the received power can be compared with calculations derived from system data, derived from antenna, amplifier, filter and cable charts.

The beacon method is ideally suited to lengthy surveys and allows the measuring system to be constantly checked during the survey period. The disadvantage of the method is that a considerable amount of test equipment is required to perform the calibration. This could cause difficulties on sites such as rooftops where the equipment will need to be transported to and where space may be limited.

This method assesses all the components in the measurement system including the antenna.

b) Signal substitution method

In this method a signal injection point is required in place of the measurement antenna to inject a known signal level from a calibrated signal generator. This method calibrates the measurement system including filters, amplifiers and feeders. The measurement antenna requires at least an annual calibration certificate from a test facility. For measurement systems fitted with horns and waveguide amplifiers a cross-guide coupler fitted between the horn output and amplifier input can be used to inject a calibration signal. The horn antenna will also require a calibration certificate from a test house.

It is desirable that the response characteristic of the antenna with connecting cable, and the gain of any pre-amplifier be known so that RF signal levels can be measured to an accuracy of from 3 dB to 6 dB.

The signal generator produces reference signals; its recommended characteristics are the following:

– spectrally-pure frequency synthesiser;

– frequency range 0.01-40 GHz;

– external pulse, AM and FM modulation;

– frequency resolution of 1 Hz;

– dynamic output level range −90 to about +10 dBm;

– harmonics < −20 dBc.

c) Measurement of a known source

When carrying out measurements with transportable equipment on locations such as high building rooftops, it is not always possible to have calibration equipment available. For basic confidence checking in such environment, it is sometimes possible to measure a known stable signal source operating in or close to the measurement frequency band. In these circumstances satellite signals can be a reliable basic calibration source.

6.4.4.4 Navigation and positioning systems

The monitoring vehicle should be equipped with a navigation and positioning system to enable accurate determination of position (geographical coordinates) and bearing of the vehicle (azimuthal orientation). A description of this system may be found in § 7.1 'Radio Navigation Satellite Service (RNSS)'.

The positioning system receiver installed in the vehicle can fulfil other tasks, current date and time information (YY-MM-DD and hh:mm:ss.sss). According to GPS.gov GPS Accuracy:

– time transfer accuracy relative to Coordinated Universal Time (UTC) of ≤ 30 ns, 95% of the time;

– User Range Error (URE) accuracy Single-Frequency C/A-Code ≤ 7.8 m 95% during normal operations over.

6.4.4.5 Rotation steering and telescopic supports

The measuring antennas may be installed directly on a bi-axial turntable (with typical characteristics of azimuth: 370°; elevation: −20° to +90°; positioning accuracy: 0.1°), which is attached to a mast. The base of the mast should rotate. The equipment should be configured for rapid set-up and dismantling for transport.

The vehicle may be fitted with telescopic or adjustable supports to ensure that the rotational plane is horizontal. The supports could be adjusted from within the vehicle. Coordination of the turntable with true north is achieved with the aid of a gyrocompass.

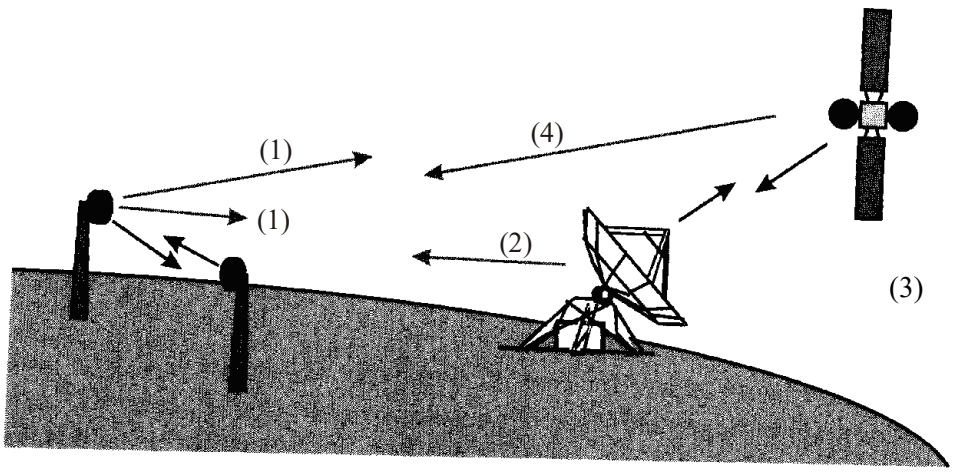
6.4.5 Fixed-satellite service sharing with the fixed service

6.4.5.1 FSS and FS interference

There are a number of standard interference paths, which are encountered in satellite and terrestrial microwave communications (see Fig. 6-97). These are controlled through various regulatory mechanisms, including frequency coordination. Normal operation of the respective links is indicated by the short solid arrows, which provide full duplex transmission.

FIGURE 6-97

Interference potential between satellite links and terrestrial microwave links that use the same frequency band



Spectrum-5.4-09

The interference paths, indicated by path numbers 1 to 4, can be described as follows:

Path 1: terrestrial radio interference into the uplink receiver of the satellite. The satellite is protected by a maximum radiated power limit of the terrestrial microwave antenna and by a stipulation that these antennas should not be directed at the GSO orbit. As a result of the low radiated power from terrestrial stations, interference of this type is not normally experienced in practice. The one possible exception is high-power tropospheric scatter links that employ billboard-sized antennas.

Path 2: Earth station interference into the terrestrial radio receiver. This is the most significant case for determining if a transmitting earth station can be operated in a particular location. The interference along Path 2 is via the side lobes of the earth station antenna and propagates along a variety of paths to the terrestrial receiver.

Administrations shall ensure that sufficient telecommand earth stations are established before launch when authorizing space stations to ensure that any harmful interference caused by emissions from the space station can be terminated immediately (see the 2024 edition of the ITU Radio Regulations (RR) No. **22.1**).

If harmful interference to the reception of any station whose assignment is in accordance with RR No. **11.31** is actually caused by the use of a frequency assignment which is not in conformity with RR No. **11.31**, the station using the latter frequency assignment must, upon receipt of advice thereof, immediately eliminate this harmful interference (see RR No. **8.5**).

Path 3: terrestrial radio interference into the downlink receiver of the earth station. The earth station antenna could be shielded from the terrestrial transmitter, a technique that has been applied to Path 2 as well. Enclosed relevant Recommendations ITU-R SA Series:

1) ITU-R SA.1273: Power flux-density levels from the space research, space operation and Earth exploration-satellite services at the surface of the Earth required to protect the fixed service in the bands 2 025-2 110 MHz and 2 200-2 290 MHz *recommends* 1 'in the band 2 200-2 290 MHz the maximum pfd produced at the surface of the Earth by emissions from a space station operating in the space-to-Earth direction, for all conditions and methods of modulation, should not exceed: −130 dB(W/m^2) in any 1 MHz for angles of arrival less than 5° above the horizontal plane; −130 + 0.5 (d − 5) dB(W/m^2) in any 1 MHz for angles of arrival d (degrees) between 5° and 25° above the horizontal plane; −120 dB(W/m^2) in any 1 MHz for angles of arrival between 25° and 90° above the horizontal plane.

2) ITU-R SA.1274 *recommends* 1 at 2 025-2 110 MHz and 2 200-2 290 MHz 'an aggregate interference power density level of −147 dB(W/MHz) from all sources should not be exceeded for more than 0.1% of the month at the input to the receiver of a spacecraft in either low-Earth or geostationary orbit;'

3) ITU-R SA.1275 *recommends* 1 'receivers onboard data relay satellites (DRS) that operate in the 2 200-2 290 MHz band which should be protected in accordance with Recommendation ITU-R F.1247 are located at the following geostationary orbital positions (given in the East direction): 10.6°, 16.4°, 16.8°, 21.5°, 47°, 59°, 77°, 80°, 85°, 89°, 90.75°, 95°, 113°, 121°, 133°, 160°, 167°, 171°, 176.8°, 177.5°, 186°, 189°, 190°, 192.5°, 195.8°, 200°, 221°, 281°, 298°, 311°, 314°, 316°, 319°, 328°, 344°, 348°.'

4) ITU-R SA.1276 *recommends* 1 'receivers onboard DRS that operate in the 25.25-27.5 GHz band which should be protected in accordance with Recommendation ITU-R F.1249 are located at the following geostationary orbital positions (given in the East direction): 9°, 10.6°, 16.4°, 16.8°, 20.4°, 21.5°, 47°, 59°, 77°, 80°, 85°, 89°, 90.75°, 95°, 113°, 121°, 133°, 160°, 167°, 171°, 176.8°, 177.5°, 186°, 189°, 190°, 192.5°, 195.8°, 200°, 221°, 298°, 311°, 314°, 316°, 319°, 328°, 344°, 348°.'

Path 2 is of concern for transmitting earth stations, while Path 3 must be addressed for any satellite receiving system on the ground.

Path 4: satellite interference into the terrestrial radio receiver. The interfering signal from a satellite is typically too weak to be of much concern to terrestrial receivers. As an example, Recommendation ITU-R SA.1273 indicates a maximum allowed pfd from the satellite on the surface of the earth; in the band 2 200-2 290 MHz.

The ITU has regulations and procedures to coordinate earth stations in one country with terrestrial microwave links in adjacent countries and vice versa (see RR Nos. **9.15** to **9.19**).

6.4.5.2 Analysis methods

In band co-channel interference to satellite communication ground stations as well as to terrestrial stations that share the same frequency bands can be evaluated by calculating the carrier-to-interference *C*/*I*. For the receive earth station geometry illustrated in Fig. 6-97, the *C*/*I* equation can be expressed in logarithmic units as follows:

$$C/I = (G(0) - G(\theta)) + (P_t - P't) + (G_s - G') - 20\log\left(\frac{R}{R'}\right)$$

where:

$G(0)$: gain of the earth station antenna in the direction of the satellite (dBi)

$G(\theta)$: gain of the earth station antenna in the direction of the terrestrial station (dBi)

P_t : transmit power of the satellite into its antenna (dBW)

P_t' : transmit power of the terrestrial station into its wanted receiver (dBW)

G_s : gain of the satellite antenna in the direction of the earth station (dBi)

G' : gain of the terrestrial antenna in the direction of the earth station (dBi)

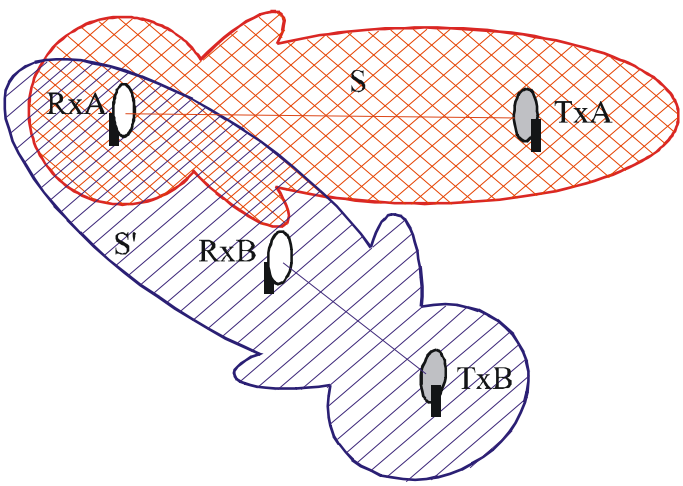
R and R' : distances between the earth station, and the satellite and terrestrial station (in the same unit).

Another method is to calculate the interference budget, which is nothing more than two link budgets: one for the desired path and the other for the undesired (interfering) path. *C*/*I* is the difference in dB between the desired and interfering received carrier powers.

Equation (5) of Report ITU-R F.2059 specifies the calculation based upon a single-source co-channel interference budget. Moreover, Figure 1 in Report ITU-R F.2059 (reproduced here as Fig. 6-98) depicts the spectrum denial area "S".

FIGURE 6-98

Spectrum denial area "S"



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An example of an interference budget is presented in Table 6-23 for the interference geometry indicated in Fig. 6-99.

There are several significant issues that arise when evaluating *C*/*I* in this manner. Some relate to the actual characteristics being modelled (e.g. the sidelobe gains of the earth station and terrestrial microwave antennas and the amount of expected terrain shielding or blockage to be realised), while others are statistical in nature (e.g. atmospheric absorption and tropospheric scatter propagation of the terrestrial microwave and satellite signals).

The analysis in Table 6-23 makes certain assumptions about the strength of the interference. The terrestrial station is 8.5 km from the earth station and the path is partially obstructed (e.g. with 20 dB of shielding). At a *C*/*I* of less than 28.6 dB, the interference would be detectable and may need further consideration. Other assumptions of a particular example are a frequency of 18.2 GHz, a diameter of the satellite dish of 3 m and a maximum gain of 39.8 dBi.

Propagation losses, other than free space loss, may represent a significant challenge for anyone estimating a realistic interference budget before field measurements can be made.

Other factors relating to earth station and terrestrial antenna performance, particularly in the back lobe and side lobe regions, are also difficult to assess.

FIGURE 6-99

Interference geometry for terrestrial interference to reception at an earth station with a large diameter antenna

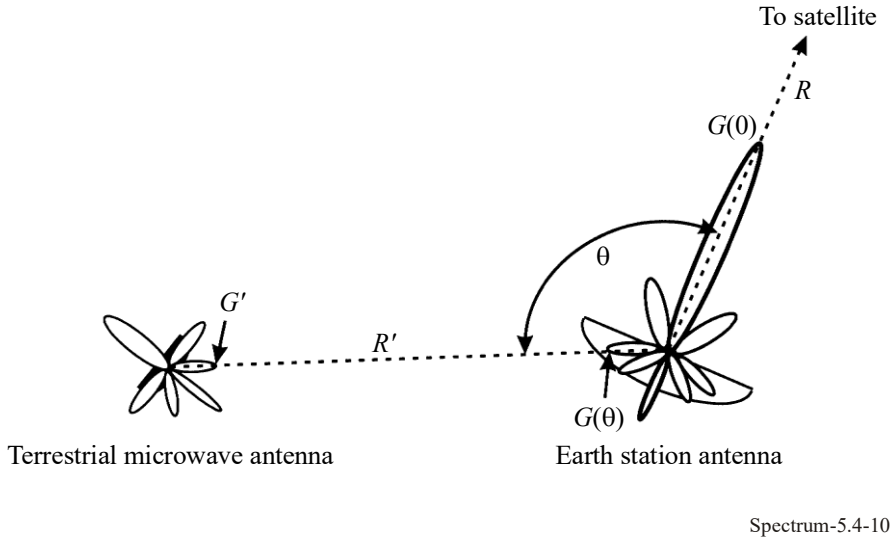


TABLE 6-23

Transmitter interference budget for a digital video link interfered by a terrestrial microwave (transmitters operate on the same frequency)

Factor	Value
Desired Signal (transmitted by satellite)	
Satellite transmit power per carrier at antenna port (W)	20
Satellite antenna gain in direction of earth station (dBi)	30
Satellite e.i.r.p. in direction of earth station (dBW)	43
Free space loss (dB)	196.2
Atmospheric loss (no rain) (dB)	0.1
Earth station maximum antenna gain (3 m dish) (dBi)	39.8
Received desired carrier power (dBW)	−113.5
Undesired signal (transmitted by terrestrial microwave station)	
Transmit power per carrier at antenna port (W)	10
Transmit antenna gain in direction of earth station (dBi)	0
Terrestrial microwave e.i.r.p. in direction of earth station (dBW)	10
Free space loss (8.5 km path) (dB)	132.1

TABLE 6-23 (*end*)

Factor	Value
Terrain shielding (dB)	20
Earth station antenna gain in direction of terrestrial microwave station (dBi)	0
Received interference power (dBW)	−142.1
Carrier-to-interference ratio (*C*/*I*) (dB)	28.6

6.4.5.3 Ground search phase of a GSO satellite interference investigation

6.4.5.3.1 General

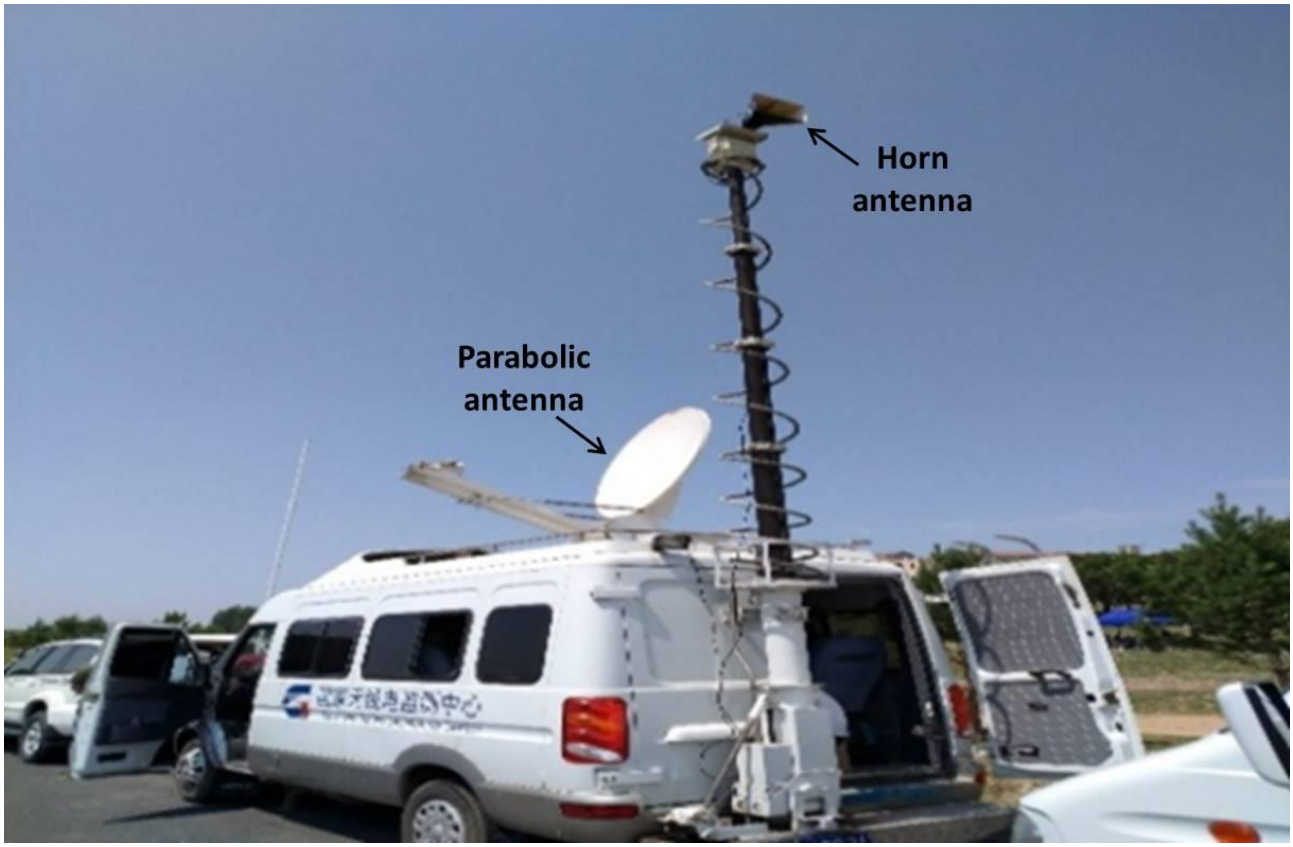
Interference poses great threat to the GSO satellite communications and broadcasts. By geolocation measurement, which is elaborated in § 6.1 of this Handbook, the interference can be located within an elliptical area covering tens to hundreds of square kilometres. This should be regarded as a great improvement comparing with the uplink coverage of the satellite within which the interference could arise. In many cases, the geolocation result will help the satellite operator identify the interferer by technical or procedure means, especially for those interfering user with faulty equipment. However, in some cases where the interferer is intentional or the satellite operator is unable to find it, an investigation known as a "ground search" becomes necessary. This poses another problem to the monitoring staff because of the difficulties to receive weak signals from the side-lobe of the interferer transmitter. These weak signals transmitted by side-lobes are normally monitored by portable equipment or equipment installed on mobile vehicles. The ground search phase of an interference investigation can be conducted by conventional approaches, or by adopting advance Digital Signal Processing (DSP) algorithms to improve the sensitivity of the measurement system. These approaches are discussed in the text below.

6.4.5.3.2 Conventional approaches using directional antennas or omnidirectional antennas

The detection of the interference can be achieved by a receiving directional antenna such as a horn antenna, LNA, and receiving equipment such as a spectrum analyser. The portable equipment should normally be carried to higher locations in order to avoid reflection to the largest extent. The operator is able to find the location of the transmitter by combining different DF results. This is a difficult task because it is usually required to conduct the measurement on top of high buildings, especially in urban areas. Another drawback is that AC power is not always available on roof-tops; therefore, long-lasting batteries are required for the spectrum analyser. Omnidirectional antenna can also be applied in the ground search. On most occasions, a monitoring vehicle equipped with receiving omnidirectional antenna, LNA and the spectrum analyser can be used to detect the interfering signal from the wanted transmitter. Two drawbacks of the omni-antenna solution should be considered by the operator, one is the lower gain of the antenna and the other is that it is only possible to conduct monitoring along the road because the equipment is typically installed on the vehicle.

FIGURE 6-100

An example of a monitoring vehicle capable of receiving signals from both space and terrestrial directions



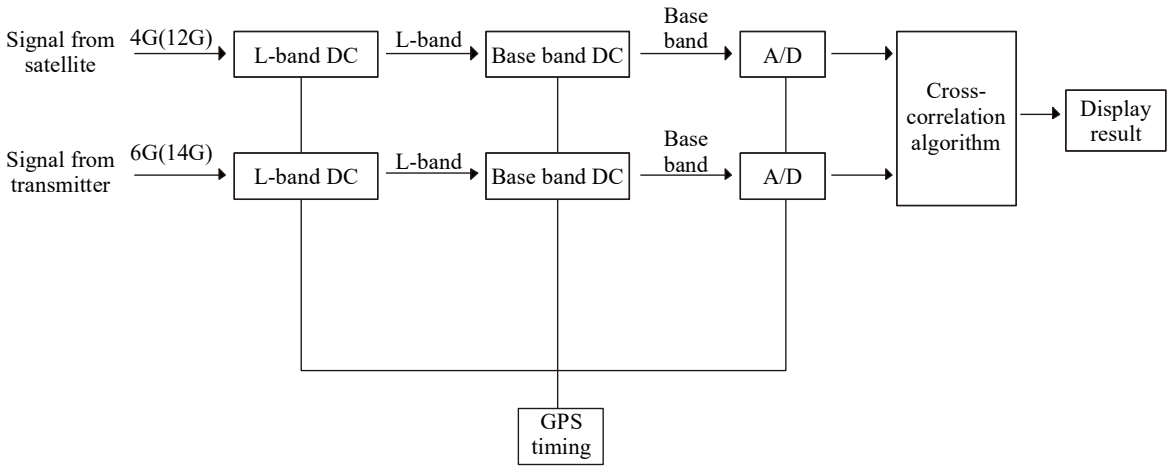
6.4.5.3.3 Using cross-correlation algorithms for improving system sensitivity

A monitoring vehicle capable of receiving signals from both space and terrestrial directions can also be used in the ground search (see for example Fig. 6-100). Instead of a spectrum analyser, DSP module is used to capture the signals below the noise floor, so that the sensitivity of the monitoring system can be improved. A block diagram of this system can be found in Fig. 6-101. In this approach, cross-correlation algorithm is utilized to process signals separately from satellite by parabolic antenna and transmitter by horn antenna or omnidirectional antenna directly.

A block diagram of this solution can be described below; Direct Current (DC):

FIGURE 6-101

A block diagram of the cross-correlation solution



Spectrum-5.4-12

In practice, the directional antenna rotates a certain angle followed by a correlation process. After rotating 360 degrees, the operator is able to find the direction of the transmitter, when the correlation SNR of both channels (space and terrestrial) maximizes, even when the level of the terrestrial signal is too weak to be observed on a spectrum analyser.

6.4.5.3.4 Using aerial platforms for RSSI measurement

The common methods for ground search of interference source include direction of arrival (DOA), time difference of arrival (TDOA) and received signal strength indication (RSSI). The DOA method requires the use of several antennas for direction finding, as well as high dependency on the monitoring equipment to obtain accurate results. The TDOA method requires precise time synchronization among different equipment. The RSSI method could be implemented by measuring signal strength, the monitoring equipment is simple and economical.

The method of using aerial platforms for RSSI measurement in the target area could effectively improve the efficiency of ground search of the interference source. A typical example using this method is shown in Fig. 6-102. The drone, as an aerial platform, is equipped with an omnidirectional antenna and monitoring equipment. The aerial platform could measure the RSSI, time and position in real time. In practice, more drones could be involved in the process.

First step: The target area is roughly divided into several grids. The drone collects a batch of new RSSI data. After that, use the difference method to estimate the grid where the interference source is mostly like to be located, and the drone flies to that target grid. Repeat the above operation until the target grid is consistent with the one where the drone is currently located.

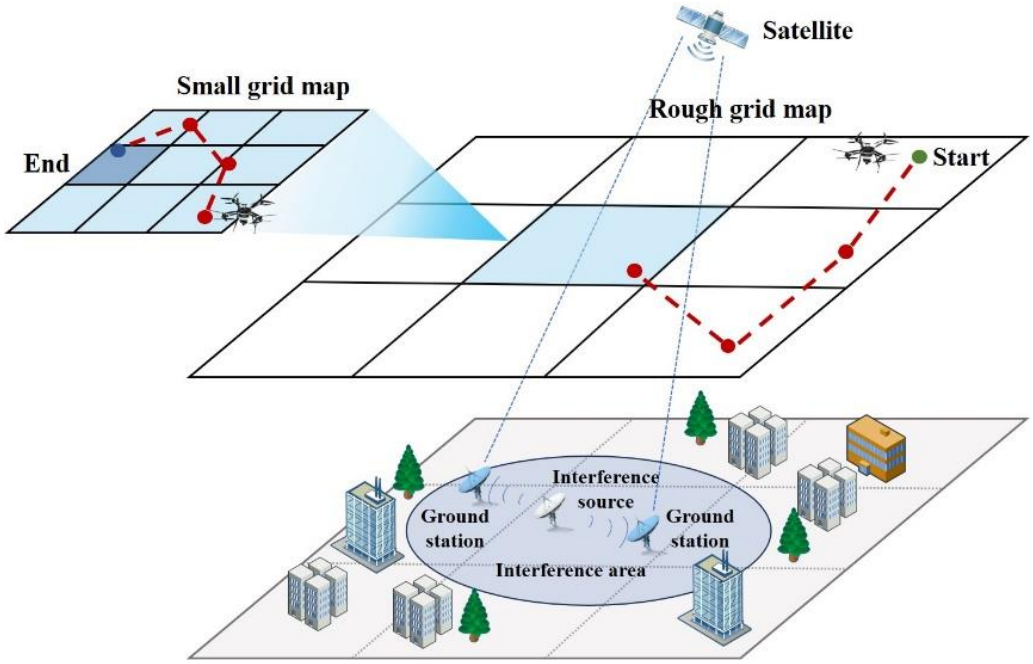
Regarding the difference method, calculate the RSSI differences at different sampling positions, convert them into the distance relationship between the sampling position and the potential position of interference source, and infer the grid where the interference source is most likely located.

Second step: That target grid is further subdivided into several smaller grids, and the drone flies and collects a batch of new RSSI data. After that, the iterative estimation algorithm is used to estimate the small target grid until it is consistent with the current position of drone. Then, the exact small grid where the interference source is located is identified.

If the operator is expected to narrow down the area where the interference source is located, the *Second step* could be repeated.

FIGURE 6-102

A typical example using aerial platforms for RSSI measurement



6.4.6 Safety

There are many safety issues associated with these types of measurements. These issues arise from both RF exposure issues (see § 6.6 'Measurements of RF-EMF human exposure levels') and the type of environments that the measuring equipment will be deployed in. A majority of the measurements will involve equipment being deployed on high building rooftops of even communication mast platforms.

There will be many hazards involved in this type of measurement. There may also be RF exposure hazards due to other microwave systems operating close to the measurement location. It is advisable that a full risk assessment is carried out before undertaking the measurement.

Each person has a duty to satisfy him/herself of safe working practices. This is particularly important when working in unfamiliar surroundings and when you may be under considerable pressure to resolve interference. Measurement staff must ensure that other people present are aware of any risks and they have taken appropriate action to protect themselves and others from such risks.

Safety is of paramount importance, not only for measurement staff, but also for all other people working or present on or near the measurement location. All cables, antennas and test equipment must be clearly marked to avoid accidents. In the case of high-power emitters, a basic RF exposure test should be conducted by measuring the field strength at the positions where staffs are operating.

Either a probe or calibrated dose meter can be used to assess the risk. If the levels are of concern, calibrated exposure measurements should be made using a minimum of personnel until the situation is quantified.

6.4.7 References

NOTE – In every case the latest editions of the Recommendations and Reports are encouraged to be used.

Related ITU-R Recommendations and Reports

Recommendation ITU-R F.302 – *Limitation of interference from trans-horizon radio-relay systems*

Recommendation ITU-R SA.1273 – *Power flux-density levels from the space research, space operation and Earth exploration-satellite services at the surface of the Earth required to protect the fixed service in the bands 2 025-2 110 MHz and 2 200-2 290 MHz*

Recommendation ITU-R SA.1274 – *Criteria for data relay satellite networks to facilitate sharing with systems in the fixed service in the bands 2 025-2 110 MHz and 2 200-2 290 MHz*

Recommendation ITU-R SA.1275 – *Orbital locations of data relay satellites to be protected from the emissions of fixed service systems operating in the band 2 200-2 290 MHz*

Recommendation ITU-R SA.1276 – *Orbital locations of data relay satellites to be protected from the emissions of fixed service systems operating in the band 25.25-27.5 GHz*

Report ITU-R F.2059 – *Antenna characteristics of point-to-point fixed wireless systems to facilitate coordination in high spectrum use areas*

Report ITU-R F.2416 – *Technical and operational characteristics and applications of the point-to-point fixed service applications operating in the frequency band 275-450 GHz*

Related ITU-T Recommendation

Recommendation ITU-T G.703 – *Physical/electrical characteristics of hierarchical digital interfaces*

ITU-R Handbooks on satellites

Handbook on Satellite Communications (FSS)

Handbook on Small Satellites

6.4.8 Bibliography

Mazar, H [2016] *Radio Spectrum Management: Policies, Regulations and Techniques*.

6.4.9 Abbreviations/Glossary

CA Channel arrangement

DOA Direction of arrival

DSP Digital signal processing

FDM Frequency division multiplex

GSO Geostationary satellite orbit

IF Intermediate frequency

LoS Line of sight

LNA Low noise amplifier

P-P point-to-point

pfd power flux-density

RR ITU Radio Regulations

RSSI Received signal strength indication

SCPC Single channel per carrier

6.5 Monitoring of radar emissions

6.5.1 Introduction

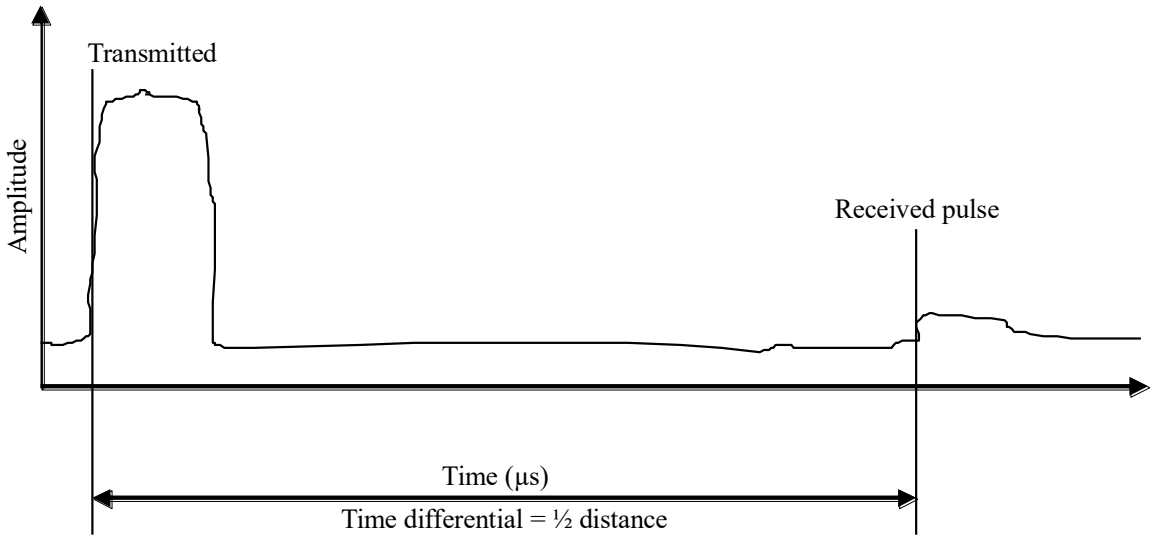
Radar, an acronym for radio detection and ranging, was first applied to military use in the 1930s to detect the presence of aircraft. Today radar applications are ubiquitous. Radar is an object-detection system which uses mainly radio waves to determine the range, altitude, direction, or speed of both moving and fixed objects. Typical properties as short pulses and rotating antennas require specific radio monitoring techniques.

6.5.2 Radar basic principle

The radar operates by transmitting an electromagnetic pulse and receiving reflected signals. When the transmitted electromagnetic pulse encounters an object – such as an aircraft, vehicle, bird, cloud, mountain, or water surface – it is partially reflected. The strength of this reflection depends on the object's radar cross-section (RCS), which represents its effective reflective area. The reflected energy radiates in all directions, including back towards the radar transmitter. The radar system then receives the returned signal, amplifies it, and processes the data for analysis.

FIGURE 6-103

Typical radar pulse



Spectrum-5.5-01

The time taken for the pulse to travel from the antenna to the target and back is measured and converted into distance, based on the known speed of electromagnetic waves. Furthermore, the receiver continuously tracks the antenna's orientation, allowing the direction of the reflecting object to be determined. For moving objects, e.g. airborne objects, the relative speed of the object causes a shift in the frequency of the reflected pulse compared to the transmitted pulse, known as the Doppler effect. The relative speed of the object can be calculated from the frequency shift. When received pulses are displayed as points on a map, a series of successive measurements can be used to determine the trajectory or direction of the object. Radars equipped with advanced signal processing capabilities can determine an object's position, size, and contours, and may also classify its type or category.

The transmitted signal consists of a sequence of pulses, typically shaped as square waves. For example, a medium-range-radar, like those used by air traffic control. This type of radar generally transmits in the 2 700-2 900 MHz frequency range and features a pulse power of, for example, 1 MW (90 dBm). The pulse duration of such a system is typically 1 µs, with the Pulse Repetition Interval (PRI) or Pulse Repetition Time (PRT) is 1 millisecond. The mean transmitter power is 1 kW, meaning that an area of 50-60 NM (93-111 km) can be covered. The minimum receivable power level may be 10^{-13} W (−100 dBm).

6.5.3 The radar range equation

The general form of the radar range equation provides the maximum distance at which a target can be detected, assuming no external interference, ideal free-space propagation, and a single antenna used for both transmission and reception.

$$R_{max} = \sqrt[4]{\frac{P_T \cdot G^2 \cdot \lambda^2 \cdot \sigma}{P_{R\,min} \cdot (4 \cdot \pi)^3}}$$

where:

P_T : Transmitted power

G : Antenna gain (transmit antenna = receive antenna; without units)

λ : Wavelength (λ and R_{max} are expressed in the same unit; e.g. *m*)

σ : radar cross-section (λ and R_{max} are expressed in the same unit; e.g. m^2)

$P_{R\,min}$: Minimum received power (P_R and P_T are expressed in the same unit; e.g. *W*).

This equation illustrates that, to double the range, it is necessary to increase the antenna gain fourfold or the transmitter power sixteen-fold. The range of a radar also depends on the cross-section of the target. Depending on the radar application, range may be increased or decreased. See Recommendation ITU-R P.525 Section 3 'The free space basic transmission loss for a radar system'.

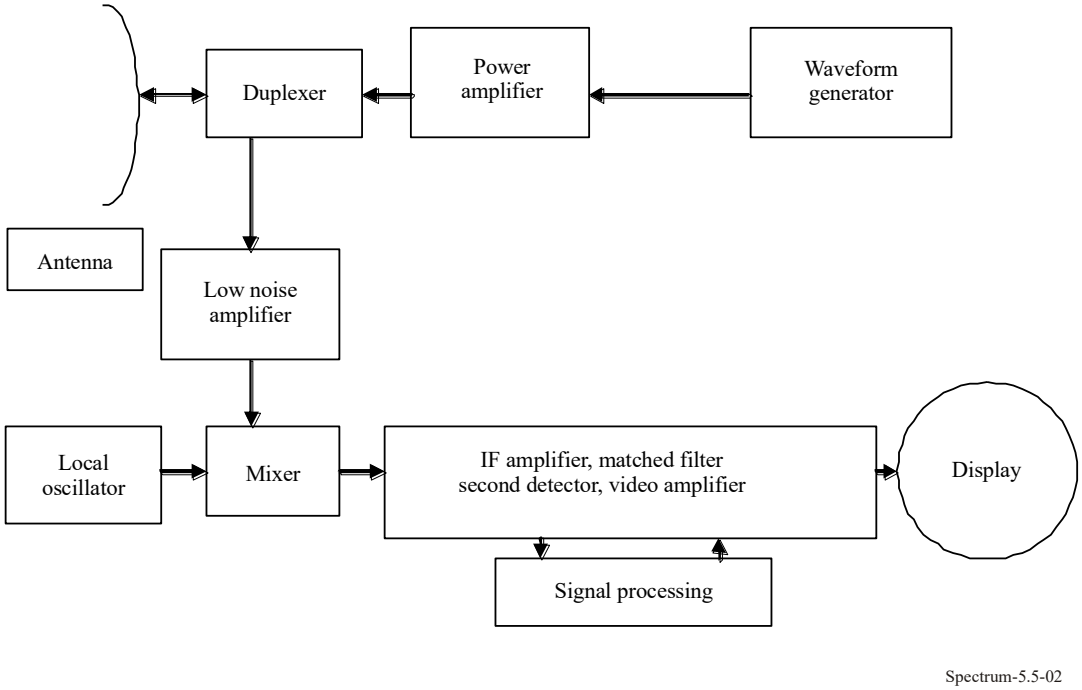
6.5.4 Main components of radar systems

The transmitter consists of a waveform generator and a power or electronic amplifier. This final stage typically consists either of a klystron, magnetron or a solid-state output stage. The multiplexer ensures rapid antenna switchover from the transmitter to the receiver and vice versa. The antenna transmits and receives the signals. In surveillance radars, the antenna is mounted on a rotating actuator equipped with a device that continuously provides the receiver with the antenna's current azimuth. In other radars, the antenna faces only one direction. The receiver must amplify the weak incoming signals and suppress the noise components, where possible.

Signal processing is used to filter out unwanted echoes (e.g. from mountains) from desired echoes (e.g. from aircraft). To achieve this, the Doppler effect – indicating the relative velocity of a moving object – is also analysed. This distinguishes moving objects from stationary ones. The antenna direction is also evaluated. All signals exceeding a preset threshold can be displayed.

FIGURE 6-104

Schematic diagram of a radar with a power amplifier



The measured data is graphically displayed on the radar screen by a visual display unit. For moving-objects both position and direction can be displayed.

6.5.5 Application of radar

Radar engineering is deployed across many services. Its main applications are aviation, navigation and the armed forces. Radar is the mainstay of meteorology (such as, precipitation or cloud radar, wind profiler). The police use radars to monitor vehicle speeds. In industry and in automotive technology radar is used for distance measurement and level sensing applications. Additionally, radar engineering plays a vital role in research and in space service, such as, earth exploration-satellite.

Radars on board ship, in harbours, locks, lighthouses

In these instances, radars determine the distance to and position of other ships, icebergs, land, etc. The frequency ranges and power levels depend on the application and size of the ship.

Radar in aircraft, on airports, etc. (air traffic control)

The radars on board of aircraft determine the distance (anti-collision radars) to other aircraft, to the earth's surface or other obstacles (radio altimeters). Many aircraft are equipped with airborne weather radars. At airports, landing and short-range radars are deployed, while long-range air surveillance radars are typically installed at elevated locations.

Radars for weather observation

Wind profilers are used to determine the velocity and direction of wind at different altitudes. Precipitation or cloud radars measure the movement of storms, accumulation of clouds and precipitation. These radars are located at airports, along with terminal doppler weather radars (TDWR) and, in larger aircraft, to issue warnings of serious turbulence.

Vehicle speed measurements

The Doppler effect is used to measure the speed of an object. Automotive radars detect the position and trajectory of surrounding vehicles, pedestrians, animals, and other objects to help prevent collisions.

Use of radars in industry, space technology, etc.

In industrial applications, radar technology is used for non-destructive testing of construction materials, as well as in level measurement and motion detection systems. It's also employed for investigating geological formations (ground probing radars). In automotive technology, distance-measuring radars are used to determine the proximity of surrounding objects. In space technology and astronomy, radar systems support remote sensing – such as planetary mapping – and the monitoring of foreign object debris.

6.5.6 Basic radar technologies

There are two basic radar technologies:

– Tube-type radars use magnetrons, klystrons, travelling wave tubes (TWTs), etc. These are still popular.

– Solid-state radar transmitters which offer advantages in cost and maintainability. These are often heavier than tube radars, and do not offer the same levels of peak power as tube radars.

– Phased-array radars consist of many small antennas, positioned in an array, next to each other. The computer shifts the phase of the original wave by fractions of a wavelength for each individual antenna in the array. The phase delays result in shifts the wave crest and trough for each antenna.

Table 6-24 shows the advantages and disadvantages of the different technologies.

TABLE 6-24

Advantages and disadvantages of different radar technologies

Radar Technologies	Advantages	Disadvantages
Magnetron	High transmitter power. Inexpensive. Large adjustable frequency range.	High noise level. Not suitable for radars with pulse compression or for using the Doppler effect (speed measurement).
Klystron and TWT	High transmitter power. Satisfactory stability. Low noise. Well suited for use with the Doppler effect.	More expensive than a Magnetron. X-radiation due to the high voltage.
Solid-state transmitters	Excellent stability. Well suited to pulse modulation and for using the Doppler Effect (speed measurement). No X-radiation. Long durability and easy maintenance (short outages).	Lower powers than those of a Klystron possible. Less energy-efficient. Often heavier and more expensive than a Klystron.
Phased-array	Similar to solid-state radars, these systems offer high resolution and rapid response times. The beamforming process enables rapid electronic steering of the beam across the sky, allowing flexible suppression of external interference.	Similar to solid-state radars, these systems also involve challenges related to cost and complexity, including high power consumption, expensive components, and advanced signal processing requirements.

6.5.7 Types or classification of radars

Radars can be classified according to very different criteria, e.g.:

– Location (on the ground, in the air, in space, on board ship, etc.).

– Frequency band.

– Function of the radar (distance measuring radar, weather radar, speed measurement, etc.).

– Signal shape (pulse, CW, FMCW).

Primary radar

The most common type of radar is primary radar, which transmits an electromagnetic signal, receives its reflection, and then processes and displays the result.

Secondary radar

Secondary radar operates by actively responding to interrogation signals. When it receives a radar pulse, it transmits a coded reply containing identification and other relevant data. This significantly extends the radar's operational range, which is why secondary radar is widely used for global aircraft surveillance. Secondary surveillance radar (SSR) is based on the military identification friend or foe (IFF), enabling to identify aircraft easier and more reliably.

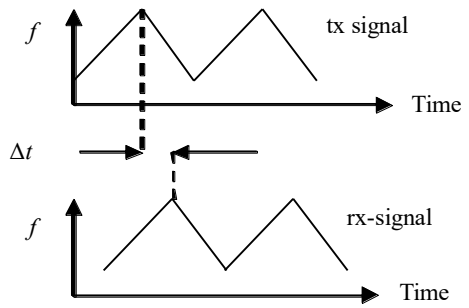
Requests are transmitted on 1 030 MHz, and the response on 1 090 MHz. Distance measuring equipment (DME) can also function–like a secondary radar. When the aircraft transmits a pulse, the ground station responds, and the time delay is used to calculate the precise distance. In navigation, the radar beacons are often installed on navigation marks. These beacons respond to radar signals with a unique code, making smaller navigational markers – otherwise undetectable – visible on the radar display.

Continuous wave radar

Continuous wave (CW) radar transmits and receives radar signals simultaneously, often on the same carrier frequency or one that is slightly shifted. It evaluates the Doppler frequency shift caused by moving objects, making it well-suited for speed measurement applications. The FM-CW radar (frequency-modulated continuous wave radar) transmits a continuous frequency-modulated signal. The signal delay causes a frequency offset which is converted into distance. This principle is used by FM-CW radio altimeters.

FIGURE 6-105

Principle of an FM-CW radar



Spectrum-5.5-03

Short pulsed radar

This is one of the most common radar applications; a short pulse is transmitted.

In this instance, the antenna is subsequently switched to receive mode and waits for a reflected signal. The direction, field strength and, often, the frequency shift (Doppler effect due to moving objects) of the received signal are evaluated.

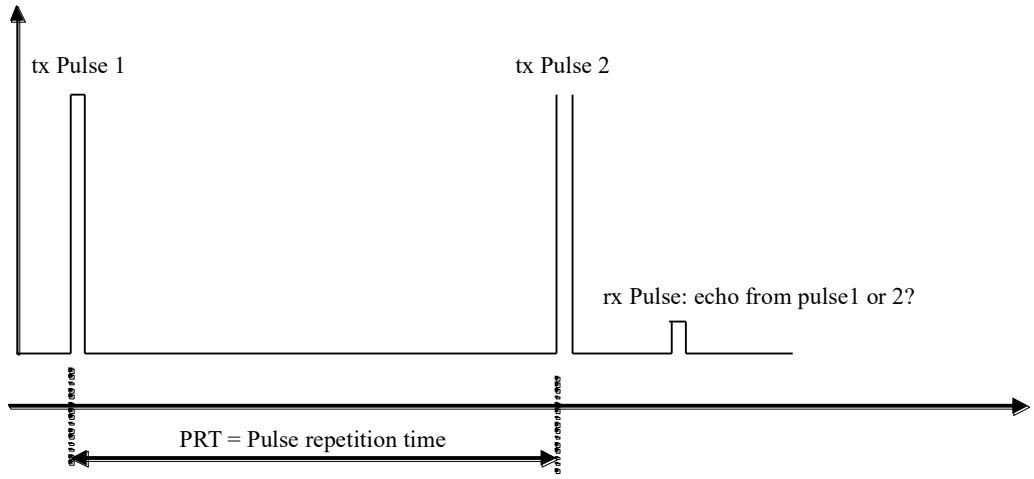
Radars used for moving target indication (MTI) employ varying PRTs or Pulse Repetition Interval (PRI), often to detect moving objects while mitigating clutter notches and correcting errors caused by long-range signal delays.

Clutter notch occurs when the Doppler effect is used to suppress fixed targets. If the relative velocity of a moving object results in a phase shift of 360 degrees or a multiple thereof relative to the transmitted wave, the object may be misclassified as stationary and consequently not displayed.

At times, it may be unclear whether a received echo is an overshoot from Pulse 1 or a valid return from Pulse 2. By varying PRIs, overshoot echoes will appear at different positions, while genuine echoes retain a consistent distance between the transmitted and received pulse.

FIGURE 6-106

Ambiguity of detected pulses



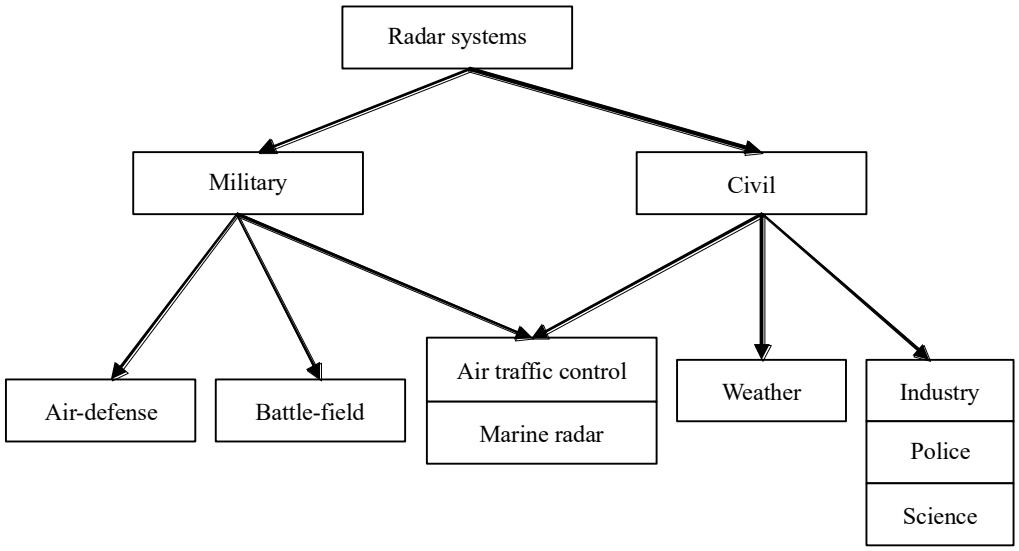
Spectrum-5.5-04

Pulse compression radar

In this type of radar, the frequency or phase of a long pulse is modulated to combine the extended range of a long pulse with the high distance resolution of a short pulse.

FIGURE 6-107

Classification according to radar use



Spectrum-5.5-05

Figures 6-108 and 6-109 illustrate some typical radars.

FIGURE 6-108

Long range air search radar and secondary-radar-antenna on the top

Spectrum-5.5-06

FIGURE 6-109

Maritime search and navigation radar

Spectrum-5.5-07

6.5.8 Main frequency bands for radar systems

Table 6-25 lists the main frequency bands for radar systems along with their application; see also Recommendation ITU-R V.431 Table 4 ‘letter designations used by some authors’.

TABLE 6-25[6]

Main frequency bands for radar systems

Part of frequency band	Band	Examples of applications in part of the frequency band
5-25 MHz	HF	Over the horizon radar
420-450 MHz	UHF	Radio location, e.g. windprofiler
1 200-2 000 MHz	L	Long range air search radar
2 000-4 000 MHz	S	Air traffic control on airports
4 000-8 000 MHz	C	Low range radio altimeter
8 000-12 000 MHz	X	Aeronautical radionavigation
12-18 GHz	Ku	Radiolocation
18-27 GHz	K	Aeronautical radionavigation
27-40 GHz	Ka	Radio astronomy
40-75 GHz	V	Earth exploration-satellite

6.5.9 Instrument to measure radar signals

The following equipment is required to conduct radar measurements:

Spectrum analyser

Many radar parameters features – such as pulse width, pulse repetition frequency (PRF), speed of rotation, transmitted power, centre frequency, occupied bandwidth and unwanted emissions can be measured using a spectrum analyser. Additionally, the analyser can evaluate rise and fall times, provided the bandwidth of the Radio Frequency (RF) filter is sufficiently wide.

Digital oscilloscope

A digital oscilloscope working in conjunction with a broadband demodulator measures the pulse duration, including the rising and declining slopes, and pulse length (also called pulse width). Many devices are fitted with special measurement functions.

Using the substitution method, pulse power can also be measured, and phase modulation can at least be identified or estimated.

A prerequisite for using the oscilloscope for these measurements is the presence of a sufficiently strong signal and the absence of other emissions at the oscilloscope input. This condition is typically met when measurements are taken directly at the radar source.

Vector signal or FFT analyser

A vector signal analyser or Fast Fourier Transform (FFT) analyser can complement the capabilities of a spectrum analyser by displaying phase or frequency as a function of time, enabling the measurement of phase and frequency modulation within a pulse. The spectrum can be captured and displayed in full after a single rotation of the radar. A spectrum analyser would require a significantly longer time to achieve the same result. Because of the special requirements described in § 6.5.10.7, an FFT analyser may not be suitable for measuring unwanted emissions in all cases.

Power meter (thermal power meter)

With a modern thermal power meter both the mean power and the pulse power can be measured direct at the measurement output of a radar. The pulse power can be calculated from the mean power, using the duty cycle.

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6 The Aeronautical Radionavigation Service (ARNS), Distance Measuring Equipment (DME) secondary radar operates in the band 960-1 215 MHz band: air search DME ground-to-air interrogator 1 030 MHz, and air-to-ground airborne transponder 1 090 MHz.

Pulse analyser

Pulse analysers scan pulses at high speed, digitize the signals and automatically process the results, and automatically process the results including frequency, amplitude, pulse width and PRF of each incoming pulse are measured.

This measurement method accurately surveys the major parameters of a radar over a short period of time. Even, staggered radars, i.e. radars where pulse length or PRI are not constant, are surveyed.

6.5.10 Measurement of radar signals

6.5.10.1 Main radar parameters

– centre frequency;

– pulse duration (pulse width);

– pulse rise and decay time;

– pulse repetition frequency (pulse rate, PRF);

– speed of rotation of the radar;

– pulse power (peak power);

– occupied bandwidth;

– unwanted emissions (spurious emissions and out-of-band emissions);

– modulation of the signal.

6.5.10.2 Measurement set-up

General

There are two principal methods to surveying a radar: directly at the radar's measurement output, or via the radio interface (free-space measurement).

To determine the speed of rotation of the antenna, the measurement must be carried out at the radio interface. This also applies when surveying the radiation pattern.

When unwanted emissions are measured at the measurement output of the radar, the exact radiation pattern behaviour of the antenna at different frequencies must be identified (see Recommendation ITU-R M.1177) as the antenna may amplify the unwanted emissions on adjacent frequencies differently from the main emission.

Not all of the smaller radars are equipped with a measurement output; in such cases the measurements must be conducted via the radio interface.

Measuring at a radar's measurement output

The transmitter power of a radar can frequently be measured via its measurement output. This is relevant to the stationary radars used in aviation, as the elevation cannot be decreased sufficiently for a direct measurement to be carried out in the main lobe.

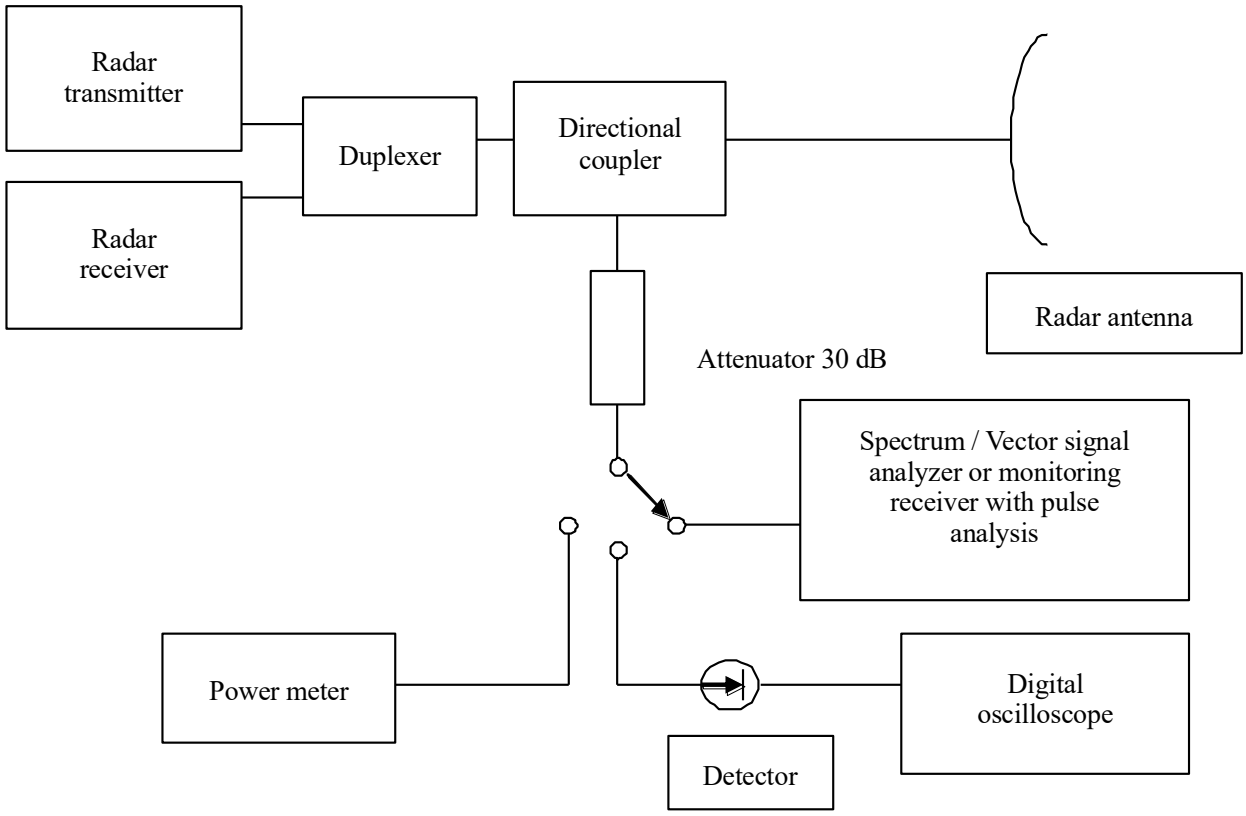
Taking measurements at the measurement output of a radar ensures that only frequency components from the actual radar are measured. This results in less problematic measurements than those via the radio interface.

However, detailed knowledge of the antenna characteristics is essential for accurately calculating transmitter power or the level of unwanted emissions.

As a result, most radars have a measurement output. A directional coupler with 30 dB coupling attenuation is inserted between the radar transmitter and radar antenna. The following Figure depicts schematic diagram for the measurement of typical radar features at the radar itself.

FIGURE 6-110

Schematic diagram for the measurement of typical radar



Spectrum-5.5-08

Measuring a radar by means of the radio interface (free-space measurement)

In this constellation, it's important to ensure that the measuring antenna is stable and oriented towards the radar's transmitting antenna (azimuth and elevation). There should be no obstacles between transmitting and receiving antenna, and far-field condition must be adhered to.

The far-field Fraunhofer distance of large antennas is derived from the following formula:

$$\frac{2D^2}{\lambda} \tag{6-22}$$

where:

D : antenna largest dimension

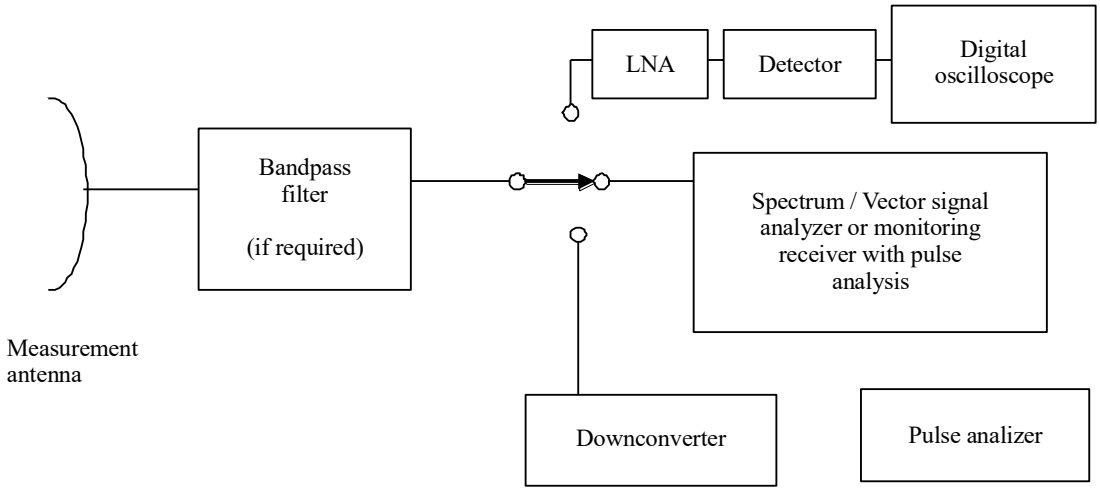
λ : wavelength of the signal; using the same units as D

For example: a long-range air search radar has an antenna diameter of 6 m and a frequency of 1 300 MHz (0.23 m). The far-field conditions are met at 312 m and beyond.

Figure 6-111 depicts an example of schematic diagram for measuring the radar by means of its radio interface (free-space measurement).

FIGURE 6-111

Schematic diagram for measuring the radar by means of its radio interface



Spectrum-5.5-09

6.5.10.3 Measurement of the centre frequency

The centre frequency is determined by operating a spectrum analyser in "positive peak" detection mode and "maximum hold" display mode over a period of time. The narrower the measurement filter (RF bandwidth), the greater the accuracy of the centre frequency reading.

The best results are achieved when each horizontal sweep point on the analyser is hit once by the maximum power of the radar. However, with a conventional spectrum analyser this process is lengthy.

For example: A long-range air search radar requires 11.6 seconds per rotation, with 500 sweep points on the analyser, the measurement takes a minimum of 1.5 hours.

The measurement duration is reduced when using a FFT analyser. The entire spectrum is displayed after a single rotation since the FFT analyser can process and display the required frequency bandwidth in a single scan.

6.5.10.4 Measurement of the pulse parameters

In this context, pulse duration, rise and fall times, PRF, and antenna rotation speed must be measured. The measurement method is largely described in § 5.9. To measure rotation speed, the analyser's sweep time should be increased until at least one full rotation is captured in zero-span mode.

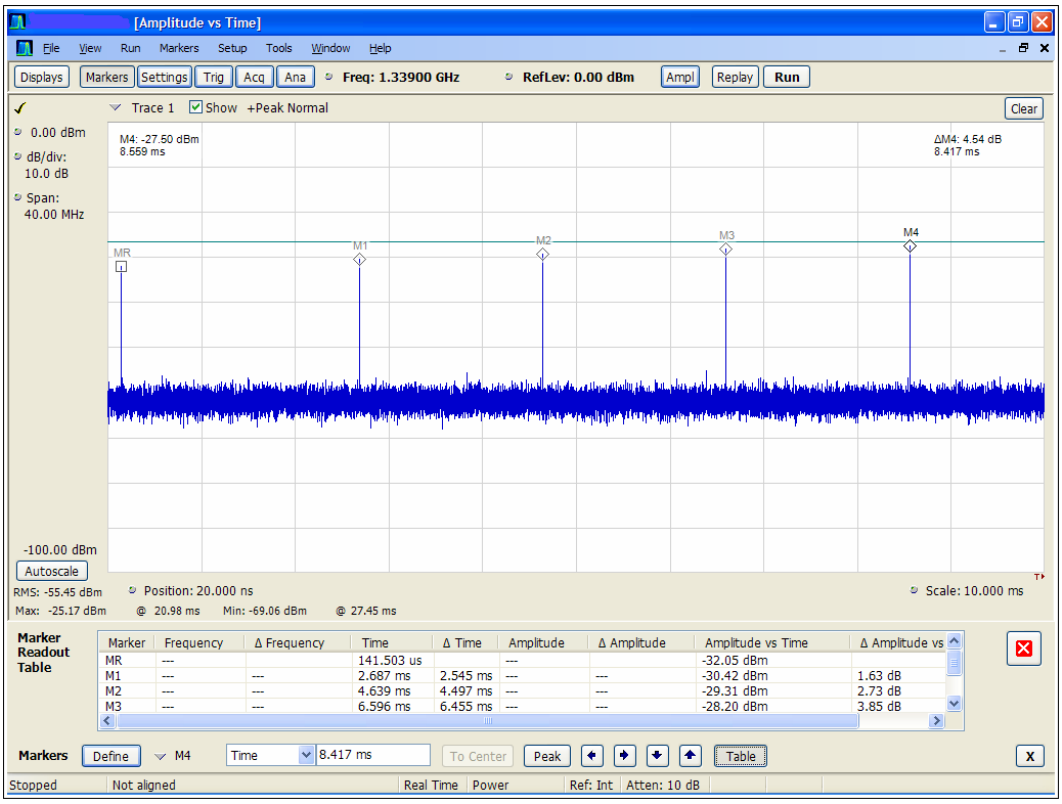
To measure a staggered radar with the spectrum analyser, several pulses need to be captured sequentially. The numbers must be sufficiently high for the PRIs to repeat themselves.

Figure 6-112 illustrates the example of a long-range air search radar applying 14 different pulse lengths. Clearly-visible on the screen is a sequence of 5 of 14 pulses at intervals of 2.545 ms, 1.952 ms, 1.957 ms and 1.963 ms.

Certainly, it is easier to use a pulse analyser for this type of measurement because the higher number of pulses that are captured (e.g. 1 024) and the pulse length, PRF and further parameters are output.

FIGURE 6-112

Pulse measurements of a long-range air search radar



Spectrum-5.5-10

6.5.10.5 Measuring the pulse power

The peak transmitter output power (or pulse power) can be measured directly at the radar, using a test coupler, either with a spectrum analyser or a thermal power meter.

Either the power meter must be capable of measuring the power solely during the pulse or the mean power and duty cycle can be used to calculate the pulse power with the formula “mean power/duty cycle = pulse power”.

For example: when the mean power of a radar transmitter is 1 kW and the duty cycle is 1/1 000, the pulse power is 1 MW.

The e.i.r.p. is determined by adding the antenna gain G_i and taking the line loss into account. If the transmitting antenna can be aligned with the main lobe direction of the receiving measurement antenna, pulse power can also be measured at the radio interface. This requires far-field conditions and a clear free-space environment.

The spectrum analyser is used for the power measurement. The pulse power and the pulse length can be measured simultaneously, see § 5.9 for pulse measurements. The radiated power is calculated using the formulae in § 7.3.2.1.

6.5.10.6 Measurement of the occupied bandwidth

Measuring the occupied bandwidth is important for assessing the unwanted emissions. According to Recommendation ITU-R M.1177, radars must not exceed a maximum bandwidth of B_{-40}, i.e. 40 dB below the Peak Envelope Power (PEP). This power is calculated from the pulse length and the rise or decay time, depending on which is shorter. The occupied bandwidth must fall within the calculated bandwidth. The formulae for the B_{-40} bandwidth measurement is described in detail in Annex 8 of Recommendation ITU-R SM.1541.

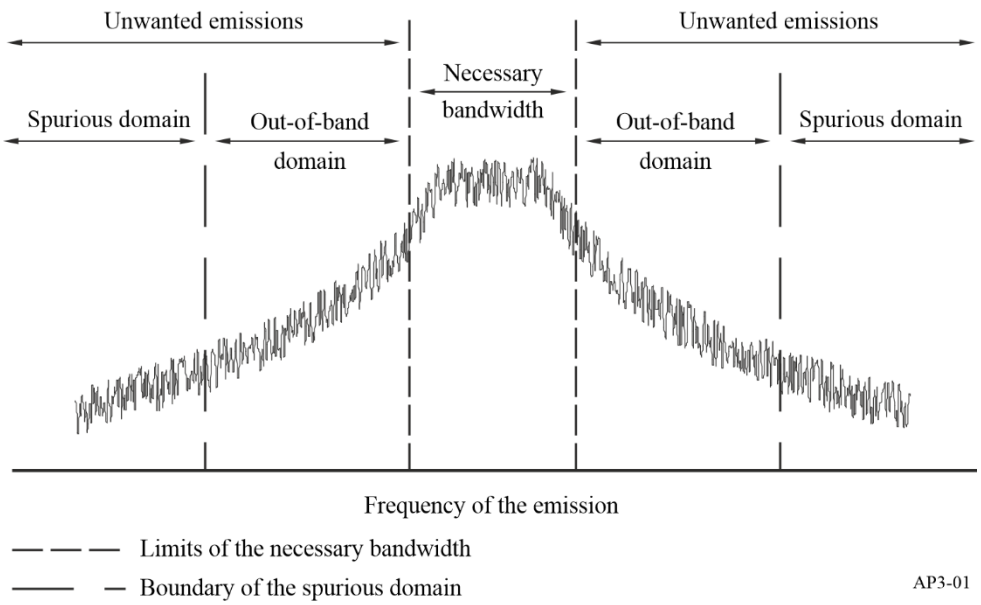
Based on ITU Radio Regulations Appendix **3** Figure 1, Fig. 6-113 depicts the domains of unwanted emissions. The emission limits are applied to all emissions, including harmonic emissions, intermodulation products, frequency conversion products and parasitic emissions, at frequencies in the spurious domain.

FIGURE 6-113

ITU Radio Regulations domains of unwanted emissions

FIGURE 1 (WRC-03)

Out-of-band and spurious domains



When measuring occupied bandwidth, it is important to consider that the maximum measurable bandwidth depends on factors such as modulation type, pulse duration, phase-chirp length and frequency sweep range. Further details may be found in Recommendation ITU-R M.1177.

According to Annex 1 to Recommendation ITU-R M.1177, a larger measurement filter than in other radio applications is used for measuring unwanted emissions and the occupied bandwidth. The calculated bandwidth B_{-40} takes into account the ensuing measurement error. For non-pulse-coded radars the measuring bandwidth B_m yields $B_m \leq 1/T$ where T = pulse length. For pulse length of 1 µs, this results in a B_m of 1 MHz. The measurement bandwidth is critical for the correct measurement of both the total level of unwanted emissions and the occupied bandwidth.

The occupied bandwidth can be measured at the radio interface and at the measurement output of a radar. Measurements at the radio interface should be carried out at a non-rotating radar antenna.

6.5.10.7 Measurement of unwanted emissions

a) General considerations

A distinction is made between unwanted emissions resulting from modulation, and those not directly related to the signal source. Unwanted emissions may include harmonic and parasitic emissions, intermodulation and frequency conversion products.

A mask which has to be adhered to and consisting of B_{-40}, out-of-band limits and spurious limits, must be calculated for each radar. This procedure is described in detail in Recommendation ITU-R M.1177; see also Recommendations ITU-R SM.328 and ITU-R SM.329.

The measurements of the occupied bandwidth and unwanted emissions are carried out with a spectrum or FFT analyser. It is important to ensure that, if an amplifier is used, it is not overloaded and that sufficient dynamic range is available for measuring the unwanted emissions. The receiver noise must be visible at the borders of the spectrum.

Figure 6-114 presents an example of a calculated spectrum mask alongside a measured spectrum from Recommendation ITU-R M.1177. For demonstration purposes the filter curve was recorded with a measuring bandwidth of 100 kHz although a measuring bandwidth close to 1 MHz would have been more appropriate. Since the measurement was carried out with a narrower measuring bandwidth, correction values have been applied in the spurious domain and for the determination of the PEP. Section 3.2.2 of this Recommendation 'Correction of the measurement data to the peak envelope power' indicates the specific Bandwidths B_{ref}, B_{pep} and B_m.

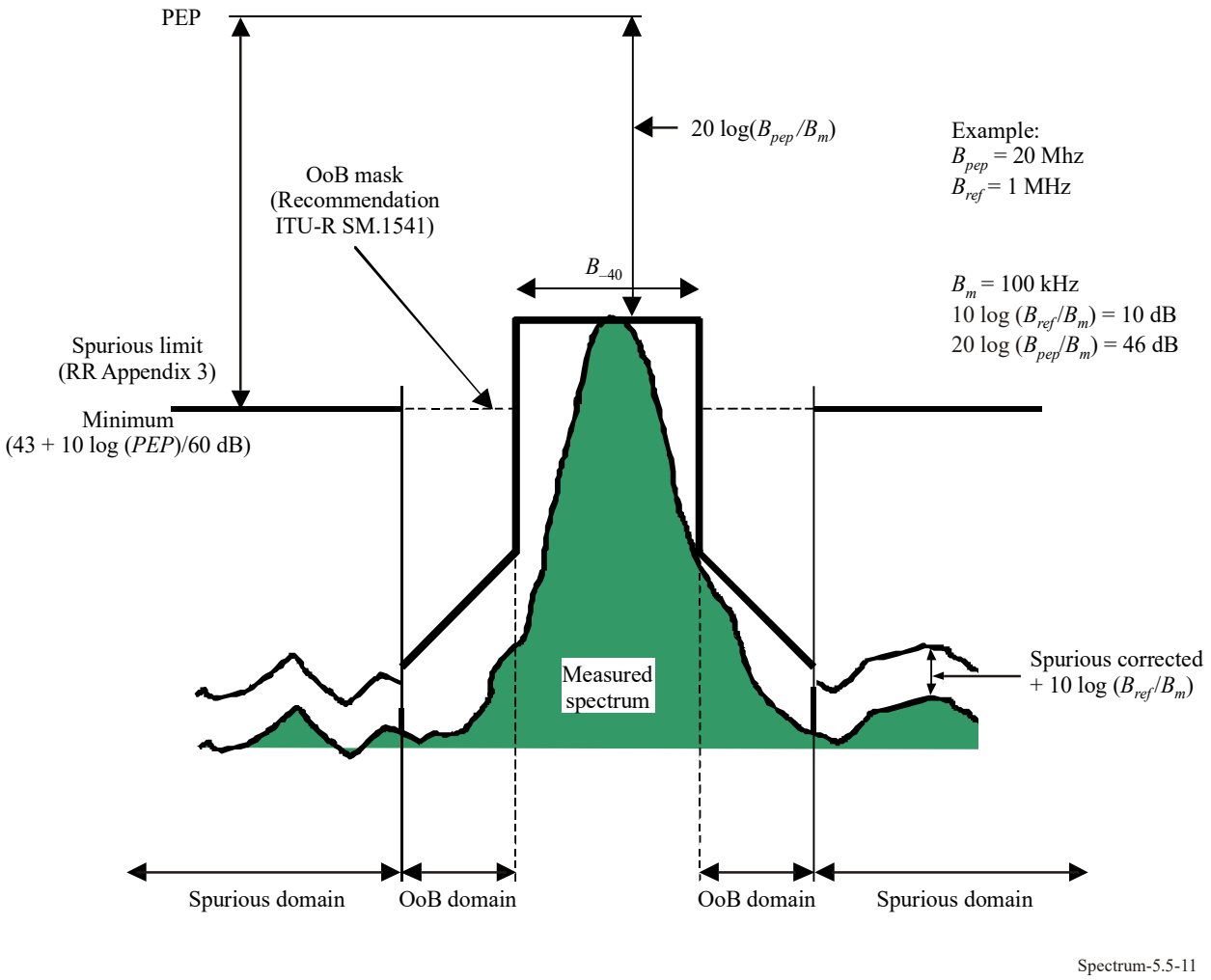
The spectrum masks for radar emissions usually span a level range of at least 60 dB, sometimes up to 100 dB. Assuming that the lowest level of an unwanted emission should be at least 10 dB above the equipment sensitivity, a minimum dynamic range of the measurement setup in excess of 70 dB (up to 110 dB) is required, which exceeds the specification of commercially available measurement receivers or spectrum analysers.

Therefore, the measurement must be performed using a filter that suppresses the main emission, while allowing the entire frequency range of interest with minimal attenuation.

For unwanted radar emissions, the measured frequency range may cover many GHz. Band reject filters (notch filters), tuned on the main radar frequency, are often unsuitable because they do not provide "near zero" attenuation over the whole frequency range. Since radar emissions – and therefore the frequency range to be measured – are typically above 1 GHz, Yttrium Iron Garnet (YIG) filters or their modern equivalents are well suited, as they are electrically tuneable and function as narrow bandpass filters. The use of these band pass filters requires a stepped measurement where the tuned frequency of the bandpass filter is synchronized with the current measurement frequency of the analyser. This requirement is best fulfilled with sweeping analysers as FFT analysers covering a wide instantaneous bandwidth may not be suitable.

FIGURE 6-114

Example of a calculated spectrum mask



b) Example of unwanted emission measurement of a radar

Taking into account information provided in § 5.12 on unwanted emission measurements, the following paragraph provides an overview of the overall approach, when an unwanted emission measurement is carried out on a radar system. This example is based on radiated measurement of a radar in the 5 GHz band on site and the rotating of the radar antenna is stopped.

Preliminary considerations

First of all, a theoretical approach is required to define and evaluate the appropriate measurement chain:

– Recommendation ITU-R SM.329 Table 1 defines the frequency range to consider (for a radar at 5.6 GHz the upper frequency of the measurement should be 26 GHz and the lower frequency is 30 MHz).

  The lower frequency forces the use of a large antenna. Given the large frequency range covered, two measurement antennas are required.

– Recommendation ITU-R M.1177 defines the measurement setup (RBW 1 MHz), a span of the applicable mask of 60 dB, and boundary limit between the Out of Band (OoB) and spurious domain.

  The mask requires a measurement chain with a dynamic range of at least 70 dB.

– Recommendation ITU-R SM.1541 Annex 8 provides some guidelines in order to define the necessary bandwidth (equal to the bandwidth at −40 dB). According to parameters of the radar in this example, B_{-40} is 15.5 MHz.

Following these considerations, a link budget must be established to identify a suitable site, taking into account the available e.i.r.p. and the dynamic range of 70 dB. This budget also permits to define the necessary gain of measurement antennas can also be defined. During the choice of the measurement site, the obstacles between line of sight to the radar antenna should also be taken into account.

The basic model also for the ionospheric propagation is the free-space. If in the 1.5 to 3 Fresnel ellipsoids no obstructions exist, the free-space propagation model can be used (see Recommendation ITU-R P.525, [Deygout, 1994] and [Mazar, 2016].

When the site is selected, a final link budget should be established to calculate the maximum received signal level at the measuring site. This information is helpful to adjust the angle of the radar antenna to optimize the dynamic range of the measurement.

TABLE 6-26

Example of link budget

Nominal power of the radar (dBm)	81
Radar antenna gain (dBi)	43.8
e.i.r.p. (dBm), taking the line loss into account	124.8
Path loss (3.3 km, free-space) (dB)	117.8
Level at the input of the measurement chain (dBm)	7
Measurement antenna gain at the radar centre frequency (dBi)	8.5
Cable loss (dB) from antenna to receiver	6
Maximum level at the input of the analyser (dBm)	9.5

For a typical spectrum analyser, the maximum input power is +20 dBm (with maximum attenuation) and the displayed average noise level in a 1 MHz resolution bandwidth (RBW) is approximately −90 dBm (without attenuation). If these conditions are met, the site is considered validated.

The principle of monitoring programs are as follows:

– configuration of the spectrum analyser (RBW 1 MHz, detector peak, trace maxhold, attenuation 0 dB);

– the frequency spectrum is divided in slices of 100 MHz;

– each slice is measured by the spectrum analyser with an integration time of 15 s;

– after each measurement, the trace data is recorded by the PC.

Measurement

Before starting, the radar should be rotated in the direction of measurement site. To optimize radar orientation, measurements are performed on the fundamental RF. The direction of the radar should be adjusted to ensure it is as close as possible to the radar power level found in the link budget.

The principle of the measurement is based on:

Step 1: Capture the spectrum of the radar signal around its central frequency.

Step 2: Carry out the measurements from 30 MHz to 26 GHz with the radar signal switched ON.

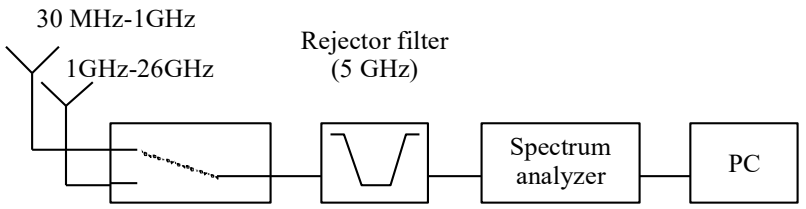
Step 3: Carry out the measurement from 30 MHz to 26 GHz with the radar switched OFF.

The first Step undertaken with a spectrum analyser (Att. max, RBW 1 MHz, Span 50 MHz, centre frequency according to the fundamental of the radar, detector peak, trace maxhold). The first recording is done.

The remaining two other steps are carried out. For these two steps, the measurement setup is illustrated in Fig. 6-115.

FIGURE 6-115

Measurement setup



Spectrum-5.5-12

Post-processing

The processing is realised in three steps:

Step 1: Level correction of the different measurements.

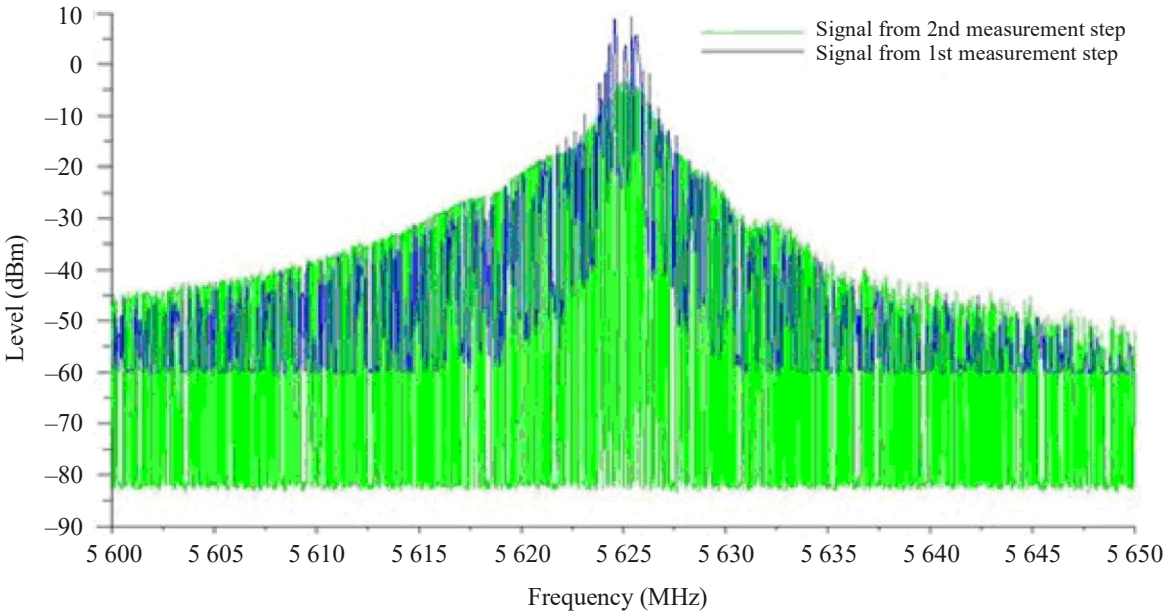
Step 2: Correlation process.

Step 3: Applying the spectrum mask to the measured radar signal.

The first step matches the level of all three measurements, and takes into account the attenuation of the filter and different attenuation of the spectrum analyser. The result of this first Step is illustrated in Fig. 6-116.

FIGURE 6-116

Correction of level at the radar central frequency



Spectrum-5.5-13

The correlation process is applied to data acquired with and without the radar signal. This Step improves the dynamic range and removes emissions which do not originate from the radar. This operation is illustrated in Fig. 6-117.

FIGURE 6-117

Correlation process

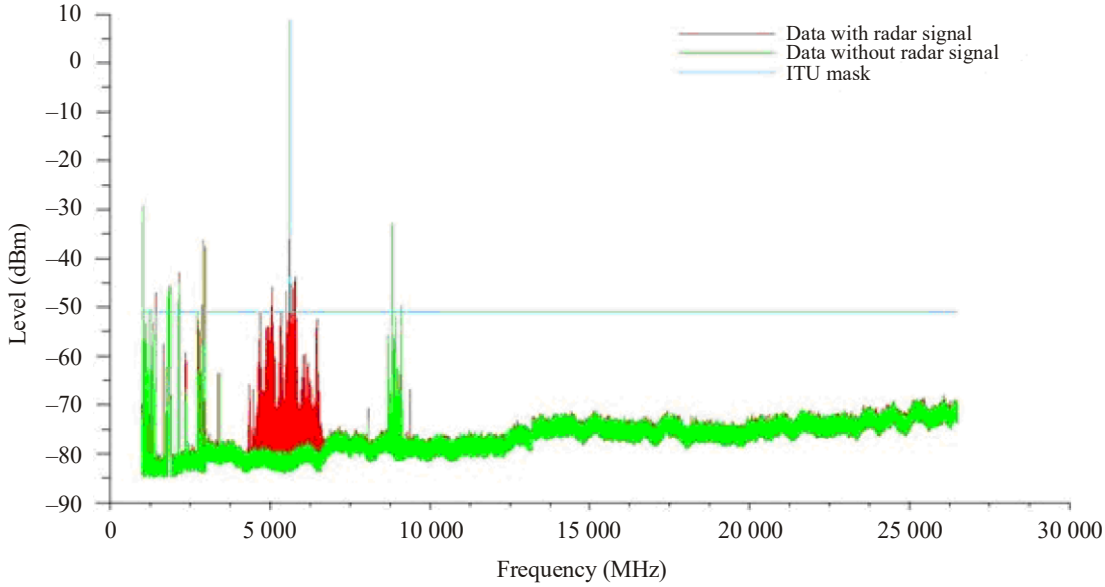
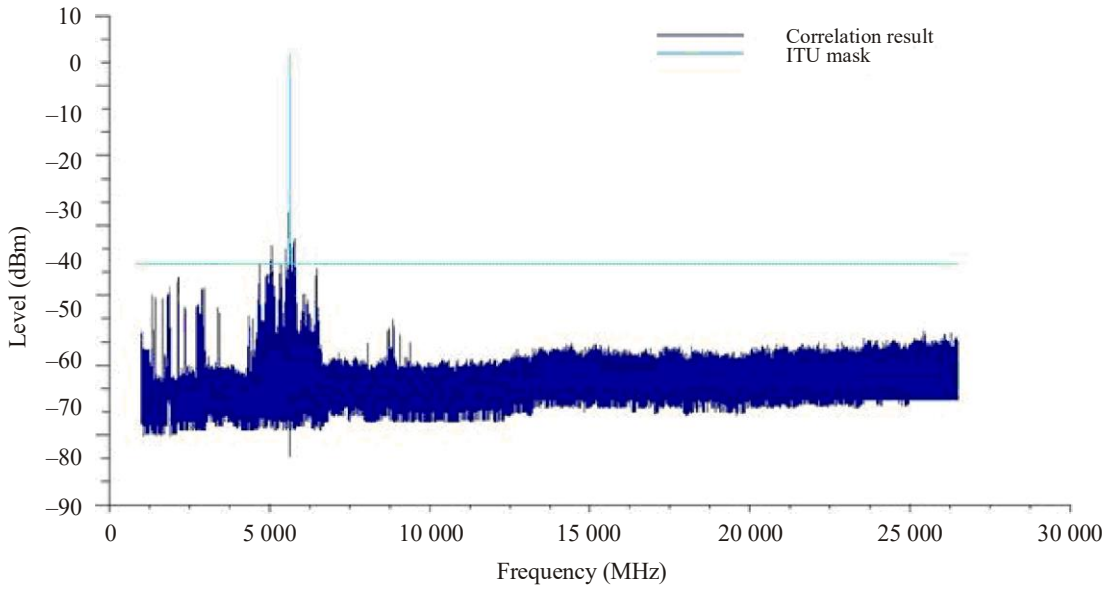


Illustration of the two series of collected data



Result of correlation process

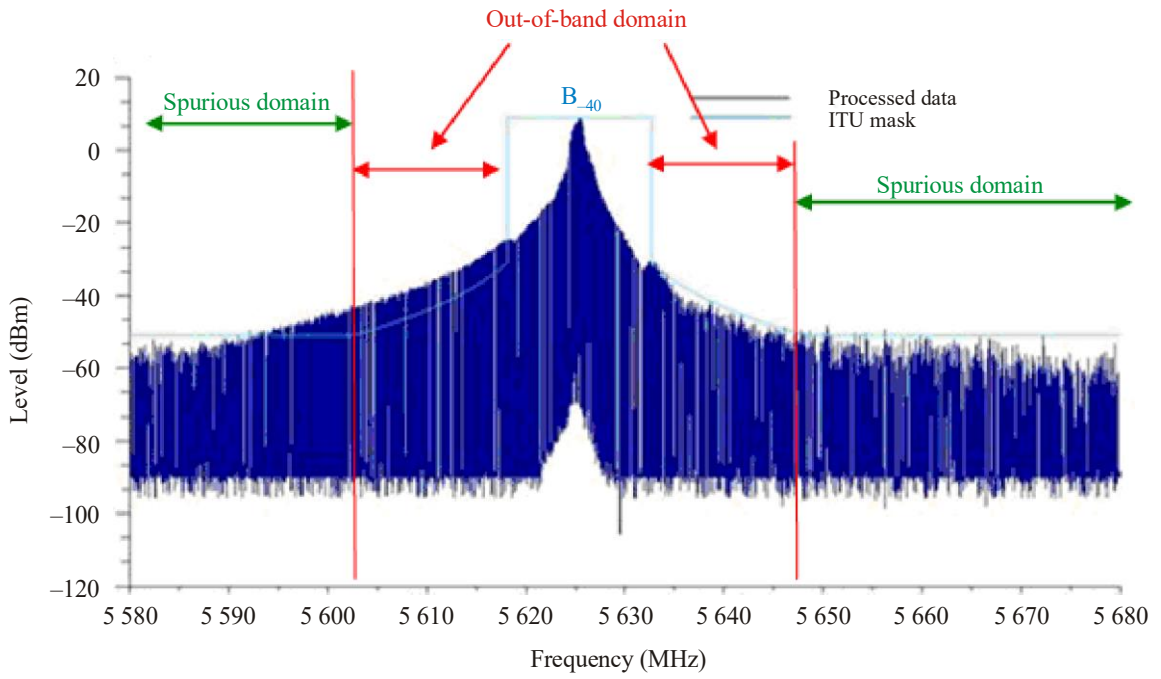
Spectrum-5.5-14

In this case, not all external signals could be eliminated. The possible reasons are the integration time being too short and the relatively long time between measurements 2 and 3.

The last Step consists of applying the spectrum mask to the processed data. This is shown in Fig. 6-118.

FIGURE 6-118

ITU mask and radar signal



Spectrum-5.5-15

6.5.10.8 Measuring the phase modulation of a pulse

Pulse compression is increasingly employed to achieve high-resolution detection, while maintaining extended radar range, through the use of long pulses; which can be achieved by phase or FM modulation of the pulse.

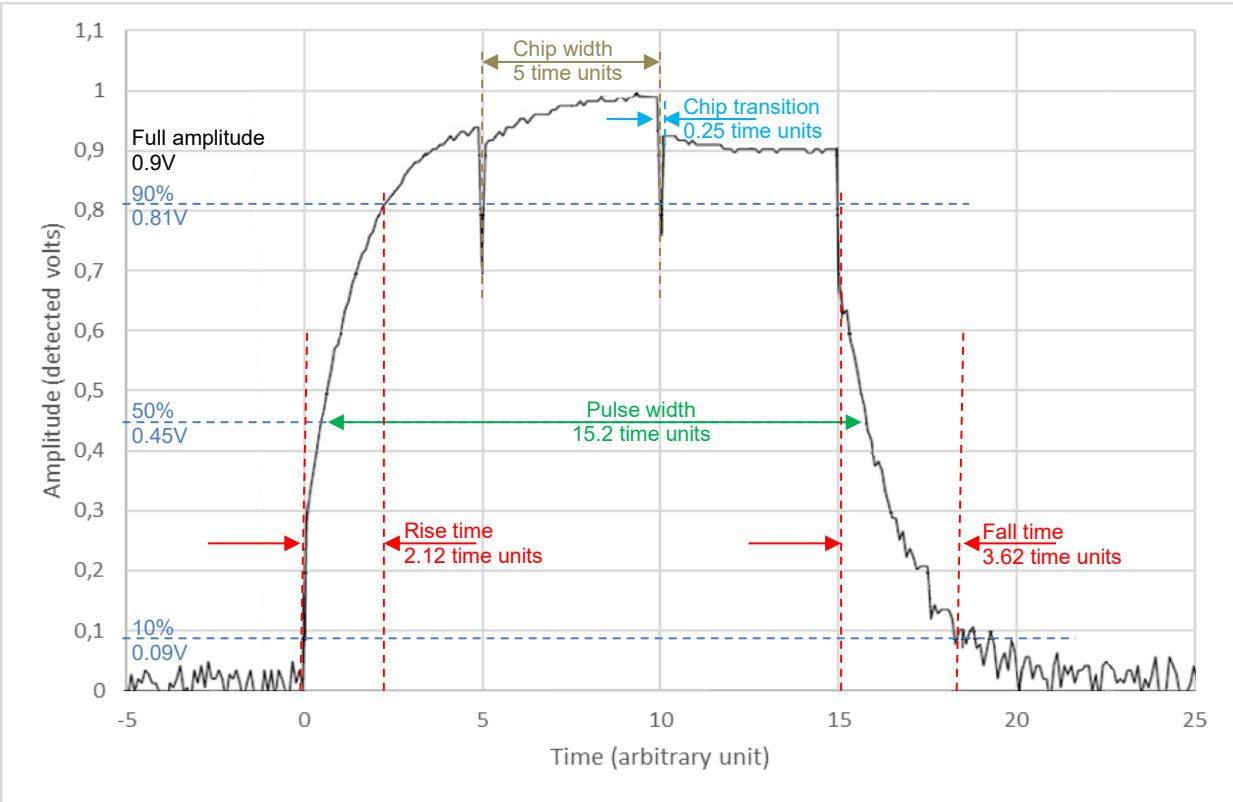
Pulse modulation can be measured using a vector signal analyser. Unlike a spectrum analyser, it displays not only amplitude versus frequency but also the phase or frequency over time.

If the phase shifts are limited, these characteristics can also be measured with an oscilloscope.

Figure 6-119 shows an example of a phase-modulated pulse with all measured parameters.

FIGURE 6-119

Example of a phase-modulated pulse with three chips



6.5.11 Abbreviations/Glossary

DME Distance measuring equipment

FFT Fast Fourier transform

PEP Peak envelope power

PRF Pulse repetition frequency

PRI Pulse repetition interval

PRT Pulse repetition time

6.5.12 References

ITU Radio Regulations

Related ITU-R Recommendations

Recommendation ITU-R F.699 – *Reference radiation patterns for fixed wireless system antennas for use in coordination studies and interference assessment in the frequency range from 100 MHz to about 70 GHz*

Recommendation ITU-R M.1177 – *Techniques for measurement of unwanted emissions of radar systems*

Recommendation ITU-R P.525 – *Calculation of free-space attenuation*

Recommendation ITU-R SM.328 – *Spectra and bandwidth of emissions*

Recommendation ITU-R SM.329 – *Unwanted emissions in the spurious domain*

Recommendation ITU-R SM.1541 – *Unwanted emissions in the out-of-band domain*

Recommendation ITU-R V.431 – *Nomenclature of the frequency and wavelength bands used in telecommunications*

NOTE – In every case the latest edition of the Recommendation is encouraged to be used.

Other References

Deygout, J. (1994), *Données fondamentales de la propagation radioélectriques*

Sanders, F. H. (2005, 1 March). *Detection and Measurement of Radar Signals*. NTIA Tutorial. National Telecommunications and Information Administration (NTIA).

Mazar, H. (2016). *Radio Spectrum Management: Policies, Regulations, Standards and Techniques*. Chapter 5: "RF Engineering and Link Budgets," Sections 5.4, 5.6 and 5.7. Wiley. Published 29 August 2016. Updated 25 October 2024.

6.6 Measurements of RF-EMF human exposure levels

6.6.1 Introduction

The increasing prevalence of mobile phones and the availability of wireless Internet go along with an increasing number of base stations. This phenomenon, associated with researches developed over the last few decades, increased the public awareness about the possible undesirable effects of RF Electromagnetic Field (EMF) non-ionizing radiation (NIR) exposures due to base stations, that may be perceived as a possible hazard to the public. This phenomenon has been of increasing concern of the public in some countries.

Studies on the hazards of EMF exposures have been conducted for many decades, and were used by the International Commission for Non-Ionizing Radiation Protection (ICNIRP) to develop international EMF guidelines in 1998. Recent studies were used to produce the latest RF EMF Guidelines 2020 "ICNIRP Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz)". In many countries[7] the ICNIRP guidelines provide the basis for the regulatory framework on this subject. The World Health Organization (WHO) "encourages the establishment of exposure limits and other control measures that provide the same or similar level of health protection for all people. It endorses the guidelines of ICNIRP and encourages Member States to adopt these international guidelines"[8].

The enforcement of regulations relating to maximum RF-EMF exposure levels from transmitters is often assigned to the authority responsible for the spectrum management, taking advantage of the existing expertise in this field. In these cases, the national monitoring and inspection services are assigned with this task of monitoring compliance with RF-EMF limits. Monitoring compliance can be done in several ways, for example, review of compliance documents or *in situ* RF-EMF measurements by the site operator, the administration or a third-party.

RF-EMF measurements may be conducted:

– in association with the issue of a radio license;

– periodically, according to a RF-EMF control and monitoring plan; or

– with good cause, i.e. due to public or official requests.

This section describes the basic principles and references for *in-situ* measurements, in order to compare with the permitted limits for human exposure. This section does not cover cases where the critical exposure is strongly localised, e.g. with personal computers, and cellular phone handsets in relation to the human head. More information on these sources may be found in Recommendation ITU-T K.91 'Guidance for assessment, evaluation and monitoring of human exposure to radio frequency electromagnetic fields' and ITU-T K.Suppl.13 'Radiofrequency electromagnetic field (RF-EMF) human exposure levels from mobile and portable devices during different conditions of use'.

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7 https://www.who.int/data/gho/data/themes/topics/topic-details/GHO/electromagnetic-fields.

8 WHO (2006). Framework for Developing Health-Based EMF Standards, pp. 7-8.

Additional significant information on characteristics of EMF, measurements (procedures and instruments), comparison between predictions and measurements, limits and levels can be found in the following publications:

NOTE – In every case the latest edition of the Recommendation is encouraged to be used.

– Recommendations ITU-T: K.52, K.61, K.70, K.83, K.100, K.156, K.113;

– Recommendations ITU-R: BT.1698-BS.1698;

– Report ITU-R SM.2452;

– IEC standards: IEC 61786-2:2014[9] (1 Hz to 100 kHz); IEC 62311:2019[10] (0 Hz to 300 GHz), IEC 62577:2009[11] (broadcast, 30 MHz to 40 GHz) and IEC 62232:2025[12,13] (base stations, 110 MHz to 300 GHz).

6.6.2 ITU three sectors, activities on EMF

This is the separation among ITU sectors D/R/T on EMF activities:

– Development (D): Strategies and policies concerning human exposure to EMF;

– Radiocommunication (R): EMF measurements from radio transmitters to assess human exposure;

– Standardization (T): Simulation, assessment (computational or measurement) of base stations, including 5G (IMT)[14].

ITU-T and ITU-R are oriented on the assessment and measurements aspects of RF-EMF, while ITU-D concentrates on strategies and policies concerning human exposure. ITU-D EMF activities were carried out during the years 2022 to 2026 in ITU-D Study Group 2 Question 7/2 'Strategies and policies concerning human exposure to electromagnetic fields'. The inter-sector cooperation on EMF improves ITU deliverables, including cross-reference citations. For more information, see the 2025 Report on Question ITU-D 7/2, titled 'Progress on strategies and policies concerning human exposure to electromagnetic fields' which is available at: http://www.itu.int/pub/D-STG-SG02.07.2-2025/en.

ITU-T activities on EMF are carried out in ITU-T SG 5 under Question 3/5. ITU-T Recommendations on EMF appear in the ITU-T K-series. ITU-T SG 5 has been particularly active in developing recommendations for protection from, and the measurement/computation of RF-EMF levels (see the list of References).

6.6.3 ICNIRP Guidelines

Table 6-27 (Table 5 of ICNIRP (2020)) details reference levels.

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[9] Measurement of DC magnetic, AC magnetic and AC electric fields from 1 Hz to 100 kHz with regard to exposure of human beings - Part 2: Basic standard for measurements.

[10] Assessment of electronic and electrical equipment related to human exposure restrictions for electromagnetic fields (0 Hz to 300 GHz).

[11] Evaluation of human exposure to electromagnetic fields from a stand-alone broadcast transmitter (30 MHz – 40 GHz).

[12] The latest version of IEC 62232 can be obtained from the IEC webstore at: https://webstore.iec.ch/en/publication/89073

[13] Determination of RF field strength, power density and SAR in the vicinity of base stations for the purpose of evaluating human exposure.

[14] See Resolution ITU-R 56-3 (Geneva, 2023) of the ITU Radiocommunication Assembly on naming for international mobile telecommunications (IMT), which states in *resolves* 1 "that the term 'IMT-2000' encompasses also the enhancements and future developments of IMT 2000 (…)".

TABLE 6-27

Reference levels for exposure, averaged over 30 minutes and the whole body, to electromagnetic fields from 100 kHz to 300 GHz (unperturbed rms values) (ICNIRP 2020, Table 5)

Exposure scenario	Frequency range	Incident E-field strength; E_{inc} (V m^{-1})	Incident H-field strength; H_{inc} (A m^{-1})	Incident power density; S_{inc} (W m^{-2})
Occupational	0.1-30 MHz	$660/f_M^{0.7}$	$4.9/f_M$	NA
	>30-400 MHz	61	0.16	10
	>400-2 000 MHz	$3f_M^{0.5}$	$0.008f_M^{0.5}$	$f_M/40$
	>2-300 GHz	NA	NA	*50*
General Public	**0.1-30 MHz**	$\mathbf{300/f_M^{0.7}}$	$\mathbf{2.2/f_M}$	**NA**
	>30-400 MHz	27.7	0.073	2
	>400-2 000 MHz	$1.375f_M^{0.5}$	$0.0037f_M^{0.5}$	$f_M/200$
	>2-300 GHz	NA	NA	10

Notes from ICNIRP 2020 Table 5:

1 'NA' signifies 'not applicable' and does not need to be taken into account when determining compliance.

2 f_M is frequency in MHz.

3 S_{inc}, E_{inc} and H_{inc} are to be averaged over 30 minutes, over the whole-body space. Temporal and spatial averaging of each of E_{inc} and H_{inc} must be conducted by averaging over the relevant square values (see Eqn. 8 in Appendix A for details).

4 For frequencies of 100 kHz to 30 MHz, regardless of the far-field/near-field zone distinctions[15], compliance is demonstrated if neither E_{inc} or H_{inc} exceeds the above reference level values.

5 For frequencies of >30 MHz to 2 GHz: (a) within the far-field zone: compliance is demonstrated if either S_{inc}, E_{inc} or H_{inc} does not exceed the above reference level values (only one is required); S_{eq} may be substituted for S_{inc}; (b) within the radiative near-field zone, compliance is demonstrated if either S_{inc}, or both E_{inc} and H_{inc}, does not exceed the above reference level values; and (c) within the reactive near-field zone: compliance is demonstrated if both E_{inc} and H_{inc} do not exceed the above reference level values; S_{inc} cannot be used below 30 MHz to demonstrate compliance, and so basic restrictions must be assessed.

6 For frequencies of >2 GHz to 300 GHz: (a) within the far-field zone: compliance is demonstrated if S_{inc} does not exceed the above reference level values; S_{eq} may be substituted for S_{inc}; (b) within the radiative near-field zone, compliance is demonstrated if S_{inc} does not exceed the above reference level values; and (c) within the reactive near-field zone, reference levels cannot be used to determine compliance, and so basic restrictions must be assessed.

ICNIRP (2010) and ICNIRP (2020) are based on two different biological mechanisms, so the averaging approaches differ:

– nerve stimulation – instantaneous below 10 MHz;

– thermal effect, produced by power over time (for frequencies above 100 kHz).

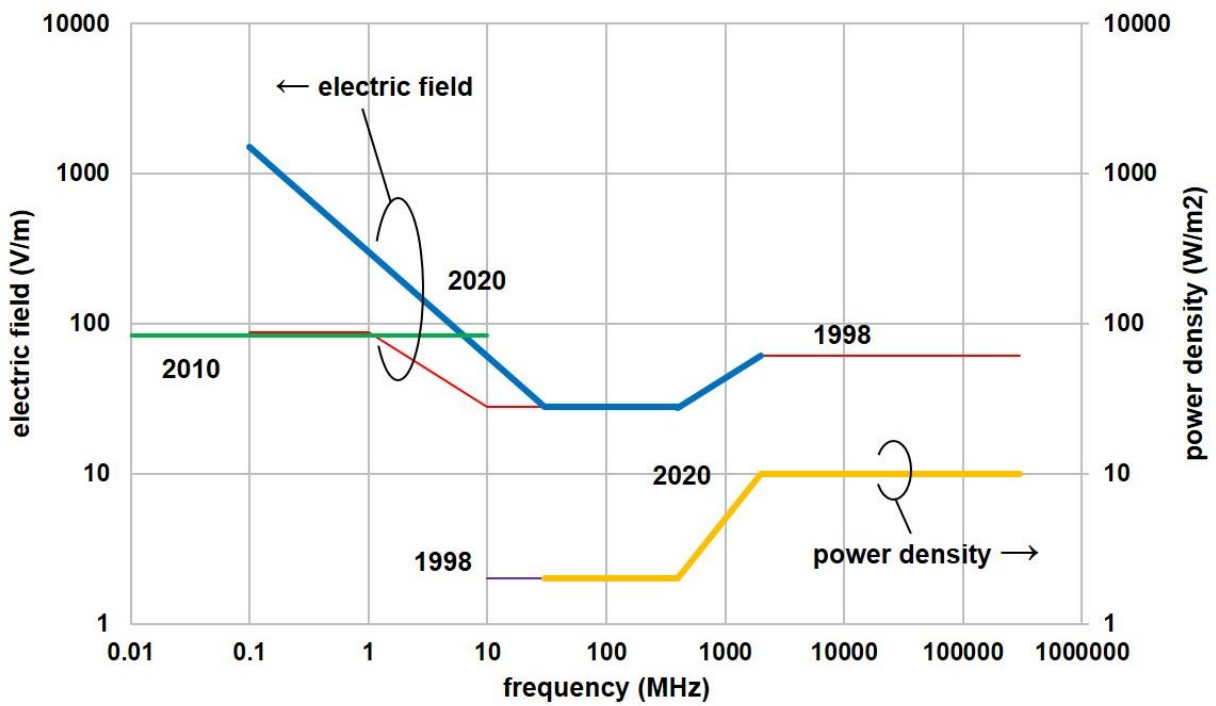
Below 100 kHz, ICNIRP (2010) should be applied. Between 100 kHz and 10 MHz both mechanisms may exist, in that case, compliance with limits on both nerve stimulation effects and thermal effects must be demonstrated.

[15] Below 30 MHz, the separation between far-field and near-field is done case by case.

Figures 6-120 to 6-122[16] depict the differences between the ICNIRP (2020) field-strength and power-density exposure levels of occupational and general-public exposure, averaged over 30 min and the whole body. The power-density ratio of 5 in ICNIRP (2020) Table 5 (e.g. at 30-400 MHz, Watts ratio 50/10) results in V/m ratio 61.0/27.7 = 2.2 ≈ √5. The following figures depict values and comparisons. As some countries apply limits from previous versions of the ICNIRP Guidelines, values from ICNIRP 1998 and ICNIRP 2010 are also shown. Underlined text indicates the significant parameter.

FIGURE 6-120

Whole body average reference levels for the general public for the ICNIRP (1998), ICNIRP (2010) and ICNIRP (2020) guidelines



[16] See Mazar 2016, Wiley 'Radio Spectrum Management: Policies, Regulations and Techniques', revised 2021 Chapter 9 figure 9.6, Report ITU-R SM.2452 (07/2022) Fig. 3, Fig. 7 and 8 (source Dr. Haim Mazar) in Background Paper, ITU Regional Forum for Europe: 5G, Strategies, Policies, and Implementation, October 2020.

FIGURE 6-121

<u>Whole body average</u> reference levels for <u>workers</u> for the ICNIRP (1998), ICNIRP (2010) and ICNIRP (2020) Guidelines

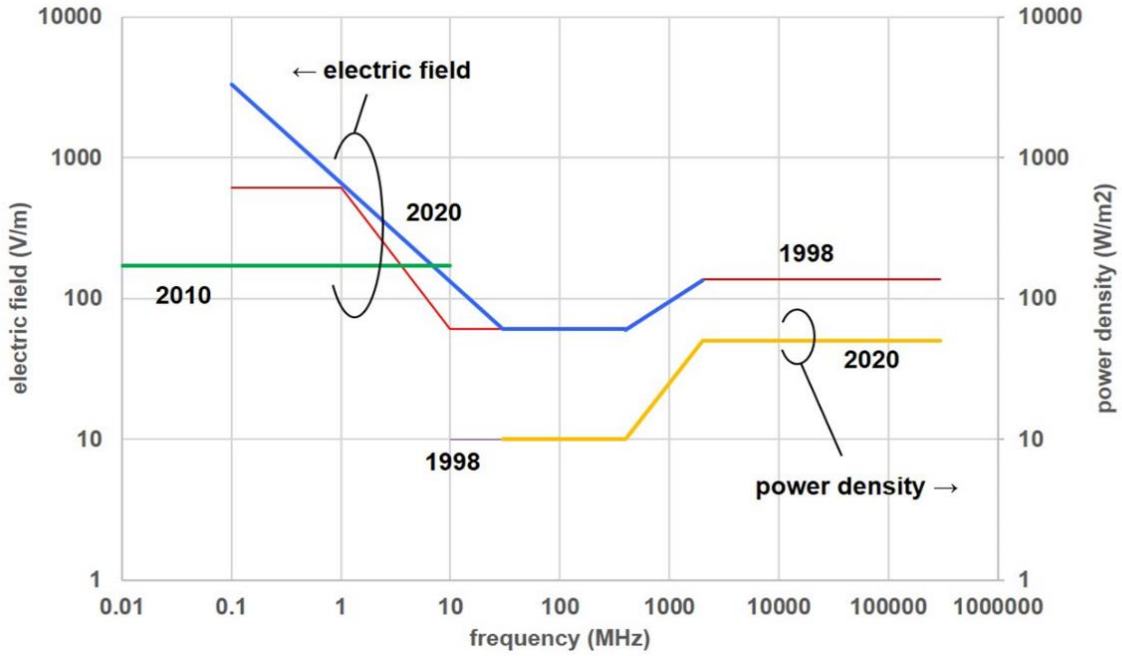
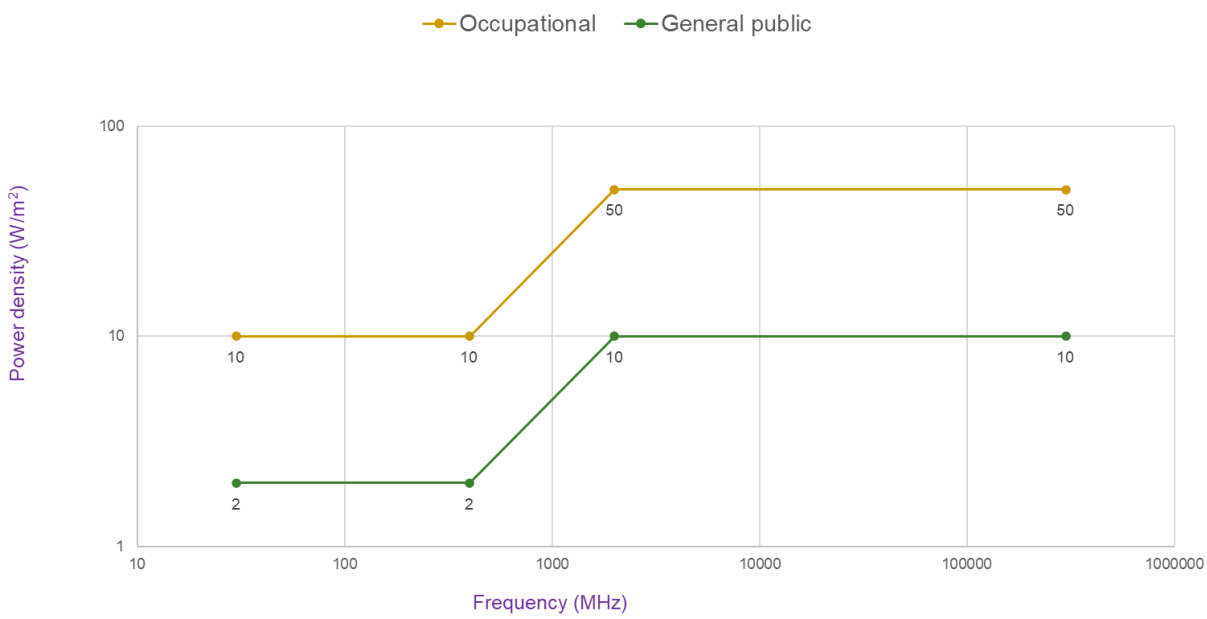


FIGURE 6-122

Comparing ICNIRP (2020) Table 5, power-density for occupational and general-public exposures 30 MHz–300 GHz, averaged over 30 min and the whole body



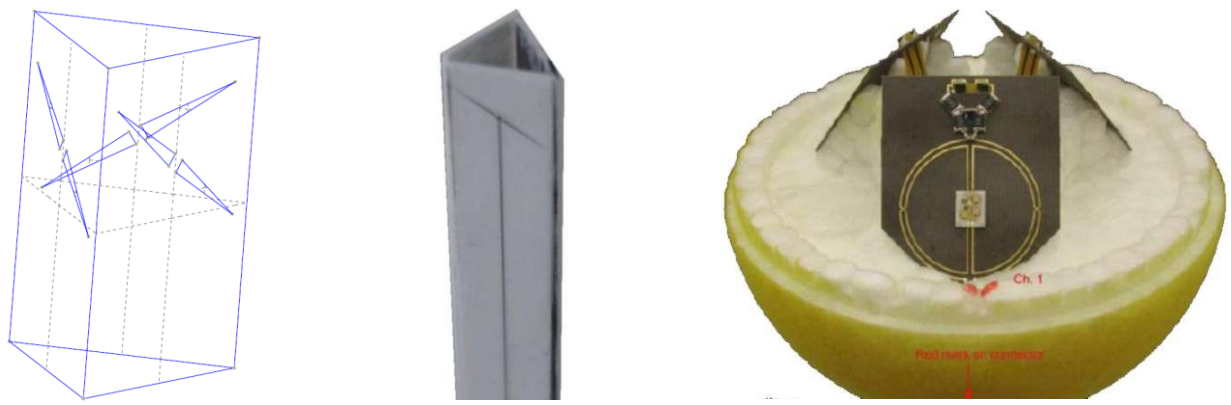
NOTE – The units of the two y-axes (i.e. incident electric field-strength and power density) are independent of each other.

6.6.4 Instruments for RF-EMF measurements

6.6.4.1 Broadband isotropic probes and meters

FIGURE 6-123

a) diagram of arrange of resistive dipoles to compose an E-field sensor; b) picture example of isotropic E-field sensor; c) picture example of an isotropic H-field sensor



a) b) c)

Spectrum-5.6-01

The isotropic probes have separate detectors for each of the three spatial components of the RF-EMF field. Usually Schottky diodes or thermocouples are applied for this purpose. With Schottky diodes a wider dynamic range can be achieved and they provide a DC level proportional to the RMS value of the RF-EMF field when they are used in the square-law section of their characteristic.

Although their sensitivity and dynamic range are lower than that of the Schottky diodes, thermocouples always provide true RMS values regardless of the RF-EMF signal waveform. So, they are better suited to measurement of RF-EMF signals with high peak to RMS ratio.

The detected DC levels originating from the different spatial components are usually combined in the instrument the probe is connected to, but in some cases, it happens in the probe itself.

Broadband probes cannot distinguish the different spectral components and produce a single measurement result. Detectors with flat frequency response provide the total field strength value in the band, but they are not suitable for the measurement of the total exposure quotient. There are probes available equipped with built-in frequency dependent weighting circuits that realize the weighting characteristic required by a particular standard. These weighted probes can provide only the value of the total exposure quotient, and are not suitable for the measurement of the total field strength.

The main benefits of using broadband isotropic probes and meters are:

– Provide fast reading, usually in the order of 1/3 of a second or less, reducing the exposure of the personal handling the equipment and allowing the use of techniques for quick overviews or monitoring while moving.

– Usually are protected against strong EMF, allowing operation near high-power radio frequency sources. Also, the upper limit of the measurement scale is usually high, more than 70 V/m and in some cases up to hundreds (V/m), allowing the evaluation of extremely hazardous RF environment, an activity that might be necessary to solve a dispute about occupational RF-EMF exposure.

– Simple to operate.

However, there are limitations:

– Whenever the probe uses Schottky diode detectors there is increased uncertainty with modulated signals and at places with multiple sources at various frequencies. As pointed out in theoretical studies [Randa and Kanda, 1985] the error can be as high −15 dB to +3 dB for energy density measurements, being typically in the order of a few dB (usually less than 4 dB). Experimentation with probes, as displayed on commercial datasheets, confirms that this error has the tendency to overestimate the real value, i.e. the displayed value is higher than the "real" EMF level.

– Presents a single value, not frequency dependent, which means that unless the equipment is used to evaluate a specific single source, the lowest limit for the frequency range covered by the probe should be used and no error correction is applicable.

– Low sensitivity, due to its broadband characteristics, the noise level for isotropic probes and meters is usually between 0.1 V/m and 0.8 V/m, which is not a problem when the lower regulatory limit applicable to general public environment is in the order of 28 V/m, such as the ICNIRP public limit (> 30 to 400 MHz), but might be a significant limitation if the applicable regulations are more restrictive. In general, is desirable that the sensitivity level should be at least three times lower in electric field terms than the intended evaluation limit.

Is recommended that isotropic probes and meters should conform with the following characteristics:

– Anisotropy better than 1 dB (deviation from ideal isotropic characteristics).

– Assess the root mean square (RMS) value of field strength.

– Maximum operational level higher than the highest regulatory limit applicable within the instrument frequency band.

– Noise level lower than the minimum regulatory limit applicable within the instrument band. 10 dB lower in power density would be the minimum reasonable requirement. If possible, this difference should be larger.

The probes must cover the full frequency range of interest, if necessary two or more probes may be required. If so, the final result will be calculated using the values provided by each probe according to the following equation:

$$E = \sqrt{\sum_{i=1}^{n} E_i^2} \text{ or } H = \sqrt{\sum_{i=1}^{n} H_i^2}$$

where n is the number of probes and E_i or H_i are the values obtained by the individual probes. Whenever multiple broadband probes are used, the result may be overestimated if the frequency ranges of the probes overlap.

If there is only a single relevant source, i.e. a short-wave transmitter at a remote location, frequency specific corrections based on calibration factors for the probe can be applied in order to improve the quality of the results.

If the results obtained are close to the lowest applicable RF-EMF exposure limit (within the range of measurement uncertainty) a frequency selective evaluation should be performed. This is especially critical for signals with complex modulation schemes, where broadband probes equipped with Schottky diode detectors might provide incorrect figures, such as previously discussed, see also [Adda *et al.*, 2023].

Based on Report ITU-R SM.2452 Section 3.2, personal EMF monitors are designed to be carried on the body of persons who are likely to be exposed to high EMF levels. The monitors invoke an acoustic, optical or vibrational alert once a certain threshold value of the actual exposure is exceeded. During measurements of the EMF exposure, also the personal which executes the measurements is likely to be exposed to high EMF levels. It is therefore a good idea to carry a personal monitor during the measurements.

6.6.4.2 Tri-axis antennas and field strength meters

Tri-axis antennas refer to specific antennas designed to perform on-site RF-EMF measurements. These usually are designed as an array of three short orthogonal antennas (dipoles, monopoles or loops). Instead of combining the RF-EMF signals from the three elementary antennas, they are sequentially connected to the output port of the antenna by a switching unit. The field strength meter (spectrum analyser or measuring receiver) performs the electric field measurements from the antenna output, for each of the spatial components. A separate external controller, such as an industrial computer or laptop, might be needed to control the antenna switching and collect the measurement data for post processing, providing a result and reports in accordance to previously defined parameters and regulations. There are solutions available that integrate the antenna switching on the antenna, and the controller on the measurement instrument used, so that it is more portable and convenient for field use.

Figure 6-124 presents an example of such measurement system such as described by [Gallee *et al.*, 2007].

FIGURE 6-124

a) System diagram including external controller, which might be eliminated if the spectrum analyser or receiver incorporate the antenna control functions; b) diagram displaying a set of short dipoles constructed to provide a near isotropic measurement characteristics; c) picture example of tri-axis short monopole antenna

Spectrum-5.6-02

The processing of the raw field strength measurements into cumulative exposure quotient, such as described in § 6.6.2, is essential to allow the proper evaluation of the measurements in accordance with the established exposure limits. This increases the importance of the tasks performed by the component above described as the "external controller" and the proper validation of the algorithms used to perform this computation.

Regarding the use of tri-axis antennas and field-strength meter, one can point to the following main benefits:

– Provide frequency selective measurements, allowing operation on multiuser (multiple signals) environment and the assessment of each spectrum user contribution. The measurement uncertainty also is usually better than observed for broadband isotropic probes, being, in general, comparable to the uncertainty observed on other on-site field strength measurement methods.

– Provide greater sensitivity than isotropic probes, in the order of mV/m, allowing the evaluation of sites subjected to much more restrictive regulations than those stated by the ICNIRP.

On the other hand, one should be aware of the following limitations:

– Slow acquisition time. Quick overviews can be performed in a few seconds, allowing the use, with caution, of methods such as stirring, but reliable measurements might take several minutes to be performed. Complete detailed scans over the full spectrum range might take closer to an hour.

– As a consequence of switching the spatial components there are short periods of time when a tri-axis antenna does not provide any output (blind periods). So, it is not suitable for the measurement of RF signals consisting short peaks (e.g. pulsed radar signals).

– Although the antenna and switching units are usually protected against strong EMF fields, the same does not hold true for the spectrum analysers and measuring receivers that usually can withstand, within manufacturer specifications, no more than 10 or 20 V/m. Most of time this is below the lowest level defined as a limit by ICNIRP. If commercial laptops or computers are used, these might also be affected by even lower levels of EMF fields.

– Due to greater complexity, the system might be more susceptible to failure especially from software components.

Based on Report ITU-R SM.2452 Section 3.2.3, the useful features for EMF measurements are:

– Handheld and battery powered;

– Immunity against high field strength levels;

– Remote control (electrical or optical);

– Direct support of isotropic antennas;

– RMS detector with configurable integration time and max-hold function in all measurement modes;

– Automatic RSS value calculation;

– Results in field strength and exposure units;

– Measurement of each service with dedicated settings;

– Demodulators for UMTS, LTE and 5G;

– Channel power options;

– Traceable calibration of the meter and the antennas;

– Frequency range at least 9 kHz to 6 GHz, preferably 9 kHz to 18 GHz or 40 GHz, to cover new wireless communication bands. Further extension by external mixers is useful for wireless systems like short range devices 60 to 66 GHz, wireless-gigabit (WiGig) devices, automotive radars and scanners.

6.6.4.3 Mobile and transportable stations

RF-EMF measuring instruments are available in manually operated (handheld or portable) forms and in versions which are suitable for autonomous operation in long term. These are referred as transportable stations.

In some countries (Brazil, Germany, Hungary; Israel, Italy, Spain (Catalonia) and Colombia), in response to public concerns, the in situ measurement of RF-EMF is complemented with the addition of transportable stations, allowing long term and/or “real time” monitoring of specific sites or, in the Brazilian case, quick overviews over large areas with the transportable station being installed on a vehicle. Analysis of data from five long-term monitoring systems operating in European countries between 2005 and 2022 shows that no values exceeded the ICNIRP public limits and that there were no significant time trends for RF-EMF levels [Iakovidis *et al.*, 2022]. More information on approaches to RF-EMF monitoring can be found in Recommendations ITU-T K.83 and ITU-T K.113.

A transportable station is composed of a RF-EMF measuring instrument, such as broadband isotropic probes or tri-axis antennas and field strength meters, associated with support sub-systems, such as special power supply, data storage and control unit, communication interface and shelter. These items are described in more detail on the following items:

– *Power supply*: isotropic probes and meters, due to their construction characteristics and broadband operation, are very susceptible to conducted noise from the power line. To reduce this noise, isotropic probes usually do not connect directly to a power line, deriving power from a DC source, such as batteries. For long term operation, such as expected for a transportable station, the power might come from solar panels or specially adapted power supplies, which provide energy to the probe by automatically switching batteries from time to time or other means, such as lasers. Stations using tri-axis antennas usually are not subjected to such problem due to the use of filters before the RF detector that reduces the interference from such sources.

– *Data storage and control unit*: Most of the stations include some sort of data storage and control unit. For systems with tri-axis antennas, usually this is an industrial PC, since the tasks of controlling and processing are more sophisticated and the volume of data is much larger. For systems using isotropic probes, this section might be much simpler; in fact, most modern portable meters already encompass memory and processing characteristics enough to handle the task of a transportable station. In both cases, is expected that such system should be able to store enough data to operate for up to a week without communication or assistance.

– *Communication interface*: Transportable stations are intended to operate while collecting long term measurements, but in several cases are also used to provide "real time" measurements for the general population in the form of RF-EMF human exposure level maps. To perform this task, some sort of communication interface is necessary. Most of the time, due to the small volume of information to be transmitted, this can be easily performed using a public wireless network. To avoid interference to the measurements, the control unit usually performs the measurement and data transmissions in sequence and at regular periods, for example, 6 min measuring + 1 min for data transmission.

– *Shelter*: Since transportable stations are intended to be installed on outside environments, they should be properly protected against humidity, heat, cold and vandalism.

Some administrations have implemented dynamic monitoring methodologies using *drive-test* techniques, avoid triaxial antenna switch not able to complete the cycle of X, Y and Z. For this purpose, mobile stations are configured with broadband isotropic probes (operating from 100 kHz to 8 GHz in Colombia) mounted on vehicles following measurement protocols as established in Recommendation ITU-T K.113. This methodology enables massive data capture across extensive urban areas; subsequently, the collected electric field strength levels are processed using geospatial interpolation algorithms.

In the Colombian context, the National Spectrum Agency (ANE), as a result of such procedures, heat maps are generated to provide a visual and technical representation of the distribution of exposure levels, allowing citizens and authorities to pre-emptively identify areas of higher or lower RF-EMF exposure within a specific geographic environment, as can be seen in Fig. 6-125. Visualization and analysis tools of this kind, enable the integration of different measurement datasets, regardless of the methodology employed by the ITU membership; hence, facilitating the dissemination of results in a clear, transparent, and accessible way. It should be noted that in the measurements carried out from 2021 to 2026, no value exceeded the limits established by ICNIRP 2020.

FIGURE 6-125

Heat maps with *drive test* measurements using transportable stations (example)

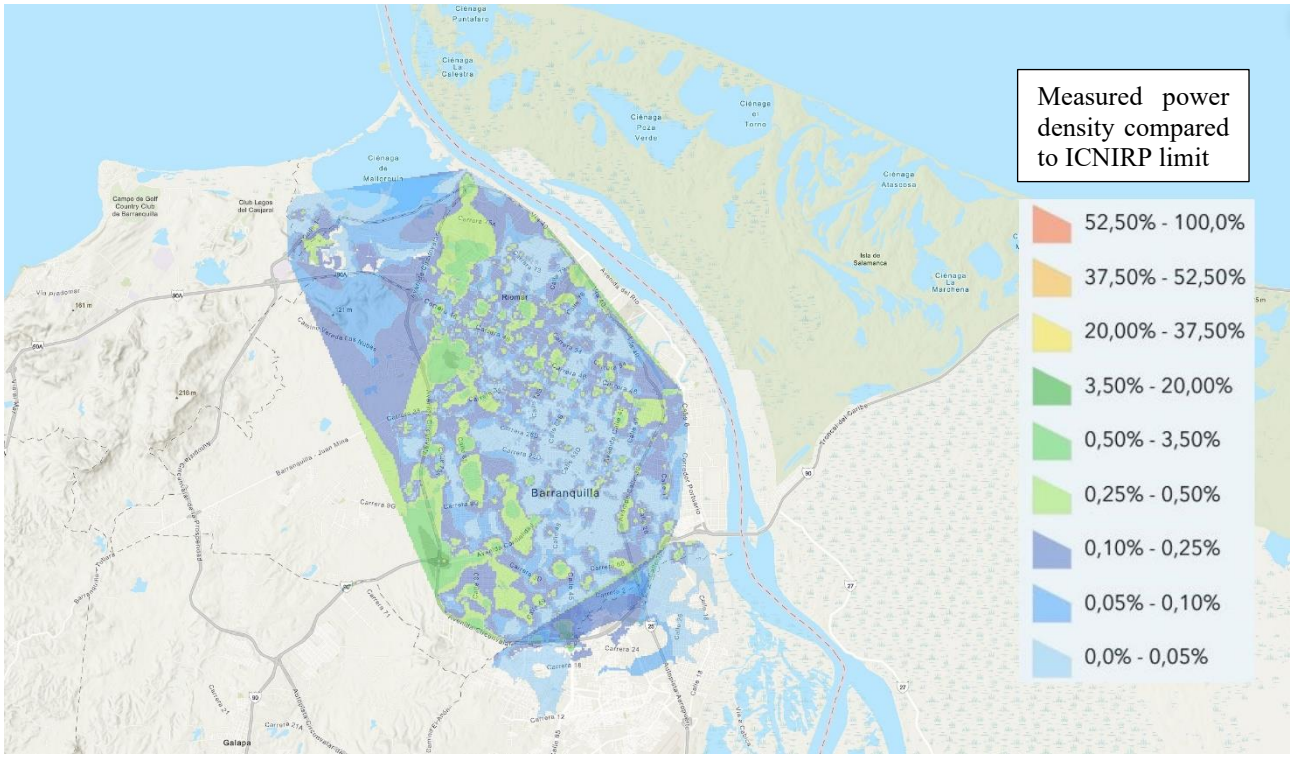


FIGURE 6-126

Transportable station

In any case, a transportable station, due to its larger size, usually does not eliminate the need for portable devices in order to properly characterize a site. Sometimes, portable equipment is also needed for an initial inspection and to determine the place where to install transportable stations.

6.6.4.4 Standard field strength measurement equipment

It is possible to use standard RF field strength measurement equipment to perform RF-EMF human exposure level measurements, including spectrum monitoring stations such as described on the other chapters of this handbook and by [Bolte *et al.*, 2016]. Such use should be made with caution, since the expected strong RF-EMF levels can damage more sensitive systems such as these, and in any case one should consider the following points.

– Due to the larger antenna size, is not possible to make near-field measurements with this equipment.

– Whenever strong fields are expected, one should use attenuators to keep the signal level from the antenna within the measurement instrument operational range.

– Measurement should be performed and computed considering all polarizations and directions in accordance with the different sources considered.

The time taken to perform RF-EMF measurements in a complex environment with standard equipment can be from four to eight times larger than the time to perform the same task with a tri-axis antenna, considering only the time needed to repeat the measurements for different directions and polarizations. This may be simplified by measuring only on the directions and polarizations effectively in use, but thus demands greater care when preparing for the measurement and on the setup.

6.6.5 Measurement procedures

The following sections provide basic guidelines that can be used to perform measurements of the RF-EMF levels.

Depending on the purpose for an RF-EMF measurement, there are three relevant measurement types:

– measurement at designated locations;

– site compliance measurements;

– measurements to protect workers.

6.6.5.1 Measurements at designated locations

This is the measurement of the total RF-EMF present at a specific, pre-determined location. Typical situations are complaints of citizens about possible high exposure (e.g. in their homes), or demands from the public for measurements at locations of community interest such as schools or hospitals. These locations are normally not dominated by emissions from one particular transmitter, but receive components from all surrounding transmitters in the vicinity. Because it cannot be assured that all relevant transmitters are active with full power at the time of measurement (e.g. nearby PMR base stations, Amateur Radio stations, …), it can only assess the RF-EMF exposure present at the time of the measurement. Long-term measurements can reveal maximum practical human exposure levels at peak times whereas short-term measurements are strictly valid only for the time of measurement.

Experience shows that this type of measurements usually results in RF-EMF levels that are significantly below the applicable limits [Jalilian *et al.*, 2019]. Exact determination of the peak times is therefore often not required. Also, no extrapolation to full traffic load is applied to mobile base stations because it cannot be assumed that all base stations in the vicinity are fully loaded with traffic during the same 30 minutes time interval.

This type of measurement can principally be performed with broadband isotropic probes. However, it is often feasible to know the main contributors to the total exposure. In this case, frequency-selective measurement devices have to be used. Another situation where the use of broadband probes for this type of measurement is not suitable is at locations with low field strengths that may be below their sensitivity, and if the measurement location is in the near-field region of a transmitter because in this case both electrical and magnetic field strengths have to be measured separately.

If the main contributors are expected to be mobile base stations or broadcast stations, specialized RF-EMF measurement equipment with isotropic wideband antennas may be used.

In other cases, it may be feasible to use standard field strength measurement equipment (monitoring receiver, spectrum analyser), because it is more sensitive and can provide valid results even at locations with low field strengths. In this case, a two-step approach will provide the most accurate results.

Step 1

A max-hold sweep with a spectrum analyser. For this step, the whole frequency range has to be separated in different frequency bands, because there is no calibrated single antenna that spans the range from LF to SHF. Table 6-28 provides guidance on practical band separation, antennas and respective analyser settings.

TABLE 6-28

Recommended settings for an overview of RF-EMF levels with spectrum analyser

Frequency range	RBW, step size	Sweep time	Antenna
9 kHz – 30 MHz	10 kHz	2 s	Magnetic loop
30 MHz – 1 GHz	100 kHz	1 s	Broadband dipole or Biconical antenna
1 GHz – 6 GHz	1 MHz	1 s	Biconical or log-periodic antenna

The detector should be peak, and the trace setting MaxHold and the sweep in continuous mode.

To find a suitable measurement point at the required location, the probe or antenna should be slowly moved through this area, avoiding close proximity to any metallic surface and also to the body of the operator, sweeping from a height of about 1.1 m up to 1.7 m from the floor. The speed of this sweep should be in accordance with the acquisition time of the sensor used. The place where the instantaneous value observed is highest should be selected.

Once a specific point is chosen for the measurement, the antennas should be mounted on a non-conductive tripod in order to reduce the perturbation of the electromagnetic field. For the same reason staff should be retreated from the antenna during the measurements. The minimum distance between the antenna and any obstacle in the direction of the transmitter (e.g. wall or ground elevation) must be at least 1 λ.

During multiple sweeps, the antenna has to be slowly turned around and all three polarization planes should be measured to capture the maximum levels. Care should be taken that any transmitting devices from the measurement crew (e.g. smartphones, Bluetooth or Wi-Fi devices) are switched off.

These settings are suitable for a general evaluation or for a quick overview of the spectrum. The peak detector with max-hold is useful to find all of the transmission sources but in this case, the calculated final total exposure quotient usually is over estimated. A threshold level is chosen 40 dB below the reference level. If no emission exceeds the threshold level within a frequency band the two highest emissions may be reported as reference. Otherwise, all emissions above the threshold should be included in Step 2.

Step 2

For an accurate result, it is preferable that the configuration parameters are adjusted in accordance with the expected RF-EMF sources, i.e. using bandwidth and sweep times matching services operating in each frequency sub-band. This is done especially in broadcast and public mobile downlink bands. The following service-independent settings are recommended:

Measurement receiver:

Frequency: centre frequency of the signal

IF-BW: bandwidth of the signal, or the next higher available filter

Detector: RMS

Meas. Time: > 10 s (see notes below)

<u>Spectrum analyser:</u>

Centre frequency: centre frequency of the signal

Span: between 1.1 and 1.5 times the signal bandwidth

RBW (resolution bandwidth): auto

Detector: RMS, or sample, if RMS is not available

Trace mode: Trace average

Meas. Function: channel power

Averaging time: > 10 s (see notes below)

Notes on measurement time:

Theoretically, the measurement time has to be chosen according to the relevant exposure guidelines, e.g. 6 min in ICNIRP (1998) or 30 min in the ICNIRP (2020) guidelines. One should be aware that although current guidelines establish a single time averaging period, this in fact should be adjusted in accordance with the signal characteristics and measurement equipment in use, for example, accommodating modulation and duty cycle of the carrier under consideration to the sweep time and detector in use. Note also that the averaging time given by the ICNIRP limits is not necessarily the same as the measurement duration, especially for constant signals or where extrapolation from a reference signal is to be implemented (see Recommendation ITU-T K.156).

Evaluation

The final result will be calculated using the values of all exposures that exceed the threshold of 40 dB below the RF-EMF limit according to the following equation:

$$E = \sqrt{\sum_{i=1}^{n} E_i^2} \text{ or } H = \sqrt{\sum_{i=1}^{n} H_i^2}$$

where n is the number of probes and E_i or H_i are the values obtained from the individual signals.

Especially for this type of RF-EMF measurement, it is often desired to calculate the percentage of the exposure limit that is used at the measurement location. This value is often easier to understand by the general public than a field strength value. As shown in § 6.6.3, ICNIRP limits depend on the frequency. This is also the case in most other standards that may be used.

If the applicable limit of all exposures selected in Step 2 is the same, the calculation of the relative exposure can simply be done using the following formulae, depending on the unit in which the limit is defined:

$$Exposure[\%] = \frac{E[\frac{V}{m}]}{E_{lim}[\frac{V}{m}]} * 100$$

$$Exposure[\%] = \frac{H[\frac{A}{m}]}{H_{lim}[\frac{A}{m}]} * 100$$

$$Exposure_{tot}[\%] = \frac{S[\frac{W}{m^2}]}{S_{lim}[\frac{W}{m^2}]} * 100$$

where:

$Exposure_{tot}$: Percentage of the limit that is used by the total exposure

E, H, S : Total electric or magnetic field strength and power flux-density measured

$El_{im}, H_{lim}, S_{lim}$: Applicable EMF-RF limits of electric or magnetic field strength and power flux-density.

NOTE – [IEC 62232] specifies that the exposure ratio is the ratio of the exposure metric and the applicable exposure limit, both expressed in terms of power.

If the exposures measured in Step 2 span a frequency range where different limits apply, their relative exposure of the individual limits have to be calculated separately. Then, the individual relative exposures have to be added using the following equation:

$$Exposure_{tot}[\%] = \sqrt{\left(\sum_{i=1}^{n} \frac{Exposure_i[\%]}{100}\right)^2}$$

where:

$Exposure_{tot}$: Percentage of the limit that is used by the total exposure

$Exposure_i$: Percentage of the exposure of one measured signal relative to its individual limit

n : Number of signals measured in Step 2.

6.6.5.2 Site compliance measurements

This type of measurement aims to determine whether a specific transmitter or shared site complies with the RF-EMF limits. The aim is to ensure that the applicable exposure limits are not exceeded at any location reasonably accessible to the general public and at any time. To achieve this result, two requirements related to the measurement have to be met:

– The measurement has to be taken at the location reasonably accessible to the public with highest possible total field strength;

– If it cannot be ensured that all transmitters on the site are operating with full power at the time of measurement, extrapolation to a full power situation has to be applied to the measurement result.

6.6.5.2.1 Selection of measurement sites

If a transmitter site is located in the vicinity of areas reasonably accessible to the public (e.g. base stations at low height, inside residential areas or on rooftops), the operator has to declare a certain area around the site as the so-called "controllable area". This means it has to be ensured that the public has no access to this area because inside the exposure limits may be exceeded. The size and shape of the controllable area have to be designed so that the RF-EMF limits are not exceeded anywhere that is reasonably accessible by the public outside this area. Typically, the highest field strengths can be expected just outside the controllable area which would be the preferable measurement locations. However, especially highly directive transmit antennas such as used in high-power VHF/UHF broadcasting and public mobile base stations may lead to points of highest field strength at street level that are much further away from the site. On the other side, there may be locations close to the transmit antennas with very low field strengths (e.g. directly underneath an antenna of a public mobile base station).

It is therefore practical to inspect the surroundings of the site with information on antenna directivities in mind when selecting possible measurement locations. Measurements at street level in the vicinity of base stations may largely underestimate the maximum exposure. The following example shows a situation with just one sector antenna of a public mobile base station located on the roof edge of a 3-story building. Measurement locations 1 and 4 are not suitable, although they are closest to the antenna, because lower field strengths may be expected compared to locations 2 and 3. However, locations 2 and 3 may not be accessible if they are on private property or require special arrangements to access, e.g. ladders.

FIGURE 6-127

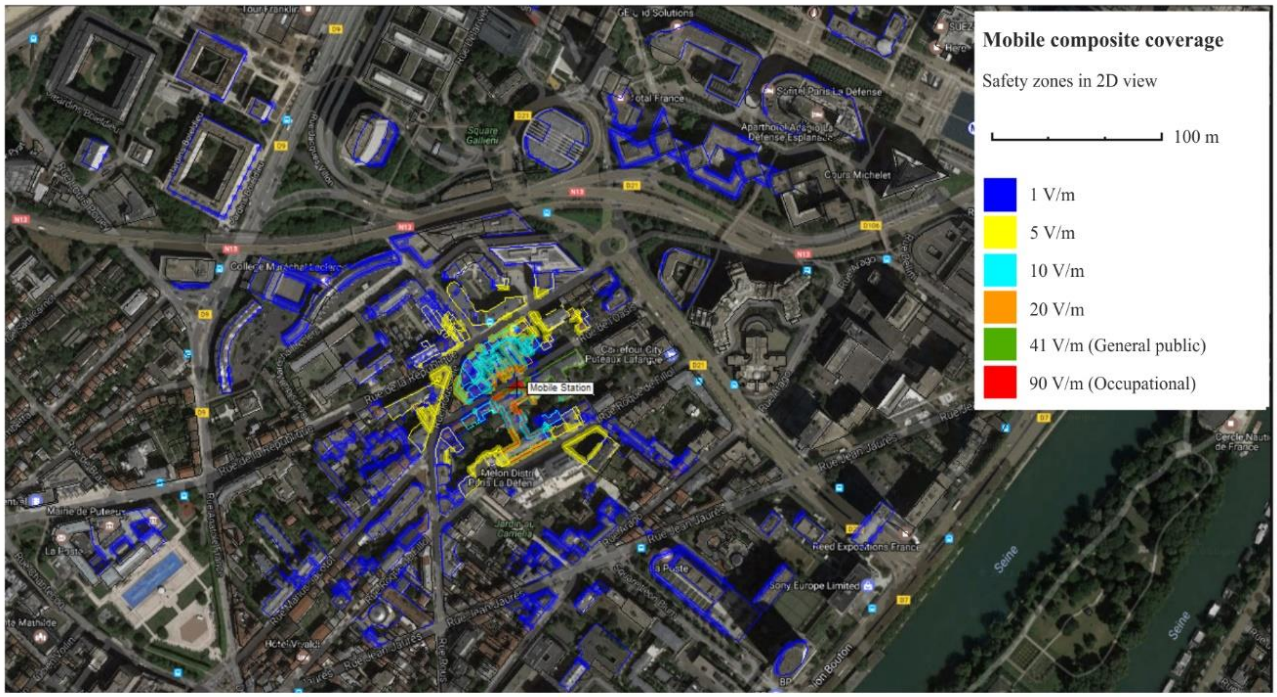
Suitability of measurement locations (example)

Computerized calculation tools such as simplified cylinder models or 3D modelling software can provide valuable information on locations with high field strengths relative to the limit values. Details on calculation procedures can be found in Recommendations ITU-T K.52 and ITU-T K.70, which includes the software EMF-estimator, one of the applications that can be used to estimate the cumulative exposure in the vicinity of transmitting stations, and K.100 for base stations.

The following example of a public mobile base station located on a roof of a city building shows regions of different field strengths calculated with 3D modelling software.

FIGURE 6-128

Calculated field strengths in the vicinity of a cellular base station (example)



Report SM.2452-06

6.6.5.2.2 Measurement equipment

Since expected field strengths at this measurement type are high, dedicated RF-EMF probes with 3-axis isotropic antennas are most suitable. Generally, these devices offer a measurement function where the field strength in all three axis are automatically added and a total human exposure level is shown, either in W/m^2, or in V/m. If different systems are in operation at the site, measurement parameters may be adjusted for each system or frequency band separately. After scanning all bands in the measurement list, a total exposure is usually calculated automatically.

Care should be taken, however, that the transmitted power of public mobile systems are traffic-dependent. The general principle for these systems is that only a traffic-independent part of the signal is actually measured and later extrapolated to a full traffic situation. To measure the required part of the signal often requires decoding functions that are usually only available as additional options. Specifics of measurement and extrapolation for such systems are explained in the following sections. Further information can be found in Recommendation ITU-T K.100 and [IEC 62232].

6.6.5.2.3 System-dependent measurement procedures and considerations

GSM

Transmissions of these systems consist of one permanent control, e.g. the Broadcast Control Channel (BCCH) channel in GSM 900/1 800 systems, and (n-1) traffic channels where n is the total numbers of channels of the base station. Hence the total power depends on the traffic load.

The following procedure can be used to assess the maximum possible traffic and thus the maximum power:

– Identify the permanent control channel.

– Set the centre frequency on the permanent control channel with a resolution equal (if possible, otherwise larger) to the bandwidth of the channel.

– Select peak detector.

– Select max-hold mode.

– Measure $E_{control\ channel}$.

– Determine the number of channels of the base station. This may be difficult in case of frequency hopping.

– The extrapolation to the maximum traffic is then calculated by:

$$E_{max} = E_{controlchannel} \times \sqrt{n_{transmitters}}$$

– If the transmitting channels of a base station are operated at different power levels, the following expression should be used:

$$E_{max} = E_{controlchannel} \times \sqrt{\frac{P_{total}}{P_{control-channel}}}$$

where:

P_{total} : maximum possible power of the base station.

CDMA systems (3G/UMTS/WCDMA, …)

RF-EMF measurements of these systems require a scanner that is able to decode the signal and perform measurements in the code domain. Taking UMTS as an example, the traffic-independent signal is the common pilot channel (CPICH), the level of which should be measured.

Extrapolation to a full traffic situation is done by adding a system-dependent factor representing the power of additional traffic channels. In UMTS, this factor is usually 10 dB, but can vary slightly according to the specific configuration of the base station.

Details of this measurement in the code domain are explained in § 6.3.4.2.

4G/LTE

For LTE (Long Term Evolution), which use orthogonal frequency-division multiplexing (OFDM) technology, two types of reproducible methods are described: one method requires the use of a dedicated decoder and another method which may be done with a spectrum analyser.

By means of an LTE decoder, the reference signal (RS), transmitted by the base station at a constant power level, is measured and extrapolated to the maximum power density.

With a spectrum analyser, the power of the primary broadcast channel (PBCH) be measured. The PBCH is transmitted every 10 ms with the same characteristics regardless of the configuration or service bandwidth and spans a bandwidth of approximately 1 MHz over the centre frequency of the LTE signal. Measurement with a spectrum analyser and extrapolation to full traffic is described in § 6.3.5.2.

For more details on measuring 4G LTE see also Recommendation ITU-T K.100.

5G/NR

This section is based on ITU-T K Suppl. 16 'Electromagnetic field compliance assessments for 5G wireless networks'. IEC 62232 specifies assessment methods for base stations and wireless networks. It covers a frequency range of up to 300 GHz and includes methodology applicable to 5G.

IEC Technical Report [b-IEC TR 62669] provides case studies for the implementation of [IEC 62232], including 5G base stations, and describes the general guidelines for the compliance of base stations using Massive MIMO (mMIMO). [b-IEC TR 62669] also includes case studies for the assessment of standalone and shared 3G, 4G and 5G base stations, and small cells.

While 5G NR base stations also use OFDM modulation, nearly all parameters are variable which makes RF-EMF measurements more challenging than LTE. A traffic-independent signal that may be used for measurements is the Synchronization and Signalling Block (SSB) which has a bandwidth of 3.6 MHz for frequency bands below 1 GHz and 7.2 MHz for higher frequency bands. However, it may be difficult to locate the SSB because it can be transmitted every 10, 20 or 40 ms, and it may be located anywhere in the frequency channel.

Furthermore, 5G NR stations especially above 1 GHz often use active antenna systems (AAS) that are able to perform beam steering. SSB and traffic beams have different antenna gains and patterns. It is therefore not only necessary to measure a certain signal part, but also to ensure that a beam is pointed towards the measurement location.

Dedicated equipment usually measures the level of the strongest SSB and uses that value for extrapolation to full bandwidth. However, this method is only valid under the following conditions:

– Traffic and SSB beams have the same power and antenna diagram, or the difference is known;
– The measurement location is within the main beam of (one of) the SSB;
– There are no considerable reflections.

In practice, especially the last two conditions can usually not be met when doing a site compliance measurement. This is because the measurement location is usually very close and often underneath the transmit antennas. Furthermore, when base stations are mounted on rooftops, a non-reflective signal path cannot be assumed. For these reasons correct RF-EMF measurements of 5G NR base stations using AAS are only possible on resource blocks (RBs) of a traffic beam attracted towards the measurement location and with probes having specific measurement functions to select the RBs with maximum level. Details are described in § 6.3.6.2.

Comparison with the extrapolated measurement result of a 5G AAS base station with the applicable exposure limits, however, may be different from the other systems. This is mainly for the following reasons:

– The concentration of RF energy towards single users through beam steering makes it extremely unlikely that a person is exposed to a traffic beam with full power for a longer time.
– It is standard for AAS base stations to apply a technology called "smart power lock", which automatically reduces the e.i.r.p. in a certain direction should a user require a signal with full power for a longer time.

Recommendation ITU-T K.100 and IEC 62232 recommend to use a certain reduction to 25-40% of the extrapolated theoretical maximum field strength (corresponding to the configured maximum power and antenna gain) when evaluating compliance with the exposure limits. These values have been derived from various measurement series.

Radar

Radars transmit in short bursts. The pulse is usually short compared to the interval between pulses.

There is a great diversity of radar, in particular for aeronautical applications. These applications have very varied characteristics, typically in frequency between 100 MHz and 95 GHz and in peak power between 1 W and 50 MW.

There may be additional limits regarding the peak power density that are relevant to radar systems. For example, the peak power density should not exceed the reference level by a factor of 30 dB according to ICNIRP (1998).

Thus, the values to be assessed for the electric and magnetic field strength are the peak values and RMS values of the pulsed field.

For the assessment of the peak value, the procedure should be in accordance with the following steps:

– Choose a sufficiently broadband filter to take measurements over one duration lower than the impulse. In the case of an unmodulated impulse, a filter bandwidth of $4/\tau$, with τ being the duration of the impulse, is sufficient to capture 99% of the power of the signal.

– Select positive peak detection mode.

– Select max-hold mode for 1 or several rotations of the radar until the signal is stable.

– Select zero span centred on the frequency of the emission.

For the assessment of the RMS field-strength it is necessary either to know the temporal characteristics of the signal and to derive the average value from the peak value or to measure the average of the signal in RMS mode.

Because of the movement of the beam in azimuth and elevation special measures have to be taken in order to measure the signal properly.

6.6.5.3 Measurements to protect workers

When strong electromagnetic fields have to be measured, safety measures against exposure of the staff above the applicable limits have to be taken. Field strength predictions, the use of RF-EMF personal monitors and explicit work instructions may be appropriate tools to ensure safe working conditions. See Recommendation ITU-T K.145 for additional information.

For this type of measurement, wideband probes such as described at the end of § 6.6.4.1 are most suitable.

6.6.6 Uncertainty

Uncertainty for RF-EMF measurement can be divided in two parts: uncertainty due to the environment and uncertainty due to the instruments.

Uncertainty due to the environment: there are uncertainties inherent to on-site measurement, due to various parameters (fading, multipath …).

This value can be reduced with the spatial averaging method as described in § 06.6.5.2.1.

One can consider that the uncertainty due to the environment is reduced to 3 dB with three measurement points and 2 dB with 6 points.

More detailed information about the application of time and spatial averaging can be found on Recommendations ITU-T K.61 and K.100.

Uncertainty due to the equipment will be intrinsic to each instrument and as such, should be provided by the manufacturer.

Care should be taken whenever buying equipment that all necessary information for the computation of the uncertainty is provided, including calibration certificates and uncertainty propagation functions that allows the proper use of the information provided on such certificates to determine the final measurement result uncertainty.

It is preferable to maintain the overall uncertainty below an acceptable level.

A target expanded uncertainty of ≤4 dB is considered industry best practice, see Recommendation ITU-T K.100 and [IEC 62232]. The same value is recommended by the European Standard EN 50492 as the maximum uncertainty.

6.6.7 Reporting

The measurement results for each location should be documented on a report, preferably using tables. The corresponding values for H (or E) and S can be calculated according to § 6.6.3, if not measured on the field.

Measured and calculated quantities have to be compared to the lowest reference level of the applicable legal provisions.

If the quantities of measured or calculated values are higher, this should be highlighted on the report and applicable provisions should be taken in accordance with the regulations in force.

Is expected that a comprehensive measurement report should also contain the following information:

– purpose and objectives of the measurements;

– date, start and stop time;

– geographic co-ordinates, altitudes above ground level, and particular characteristics of the measurement sites;

– list of identified transmitters;

– the used equipment and its serial numbers;

– uncertainty of the measurements.

Additionally, in order to improve the intelligibility of the report is desirable to use graphical representation of the results in the form of maps, diagrams and photos.

These may present the measurement results in respect of location and also the relative position of main transmitters and areas of particular interest such as schools, hospitals and houses.

Finally, the report compares the measured values with the applicable total exposure quotients and draws a conclusion on the conformity of the RF-EMF exposure with respect to the limits in the relevant regulations. Comparisons with limit values should be done on the basis of power density or the squared field strength value compared to the appropriate limit.

6.6.8 References

2025 Report on Question ITU-D 7/2, titled 'Progress on strategies and policies concerning human exposure to electromagnetic fields' available at: http://www.itu.int/pub/D-STG-SG02.07.2-2025/en.

Background Paper: ITU Regional Forum for Europe: 5G, Strategies, Policies, and Implementation, October 2020.

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European Recommendation, 1999/519/EC, 12 July 1999.

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6.6.9 Abbreviations/Glossary

3G	3rd Generation
4G	4th Generation
5G	5th Generation
EMF	Electromagnetic field
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEC	International Electrotechnical Commission
IMT	International Mobile Telecommunications
LTE	Long term evolution
RMS	Root mean square
SG	Study Group
UMTS	Universal Mobile Telecommunications Service
WHO	World Health Organization
WCDMA	Wideband code division multiple access

6.7 Radio noise measurements

6.7.1 Introduction and background

Radio noise levels set the performance limits of radio systems. Noise levels in an environment that are above the minimum sensitivity of radio receivers are highly undesirable and can result in increased cost of wireless systems deployment and operation. It can lead to interference resulting in spectrum pollution, reduced service coverage, poor quality of service and shorter battery life of devices.

Radio noise measurements are necessary for the following reasons:

– To provide up-to date values for the noise level in order to allow realistic network planning.

– To assess the system performance of existing networks in different surroundings or at specific locations.

Measuring radio noise, however, can be a very difficult task, and the level may not be the only parameter necessary to fully characterize it. This subchapter provides necessary background information on the complex issue of radio noise measurements, whereas recommendation on actual measurement setup, equipment characteristics, the measurement procedure, evaluation and presentation of the results is described in all detail in Recommendations ITU-R SM.1753 and ITU-R SM 2093.

It should be noted that methods to measure and evaluate radio noise are under constant development and the reader is advised to look at ITU-R Study Group 3 relevant Recommendation(s) and/or Report(s). Practical measurement campaigns are leading to the development of improved systems and means to visualize the results.

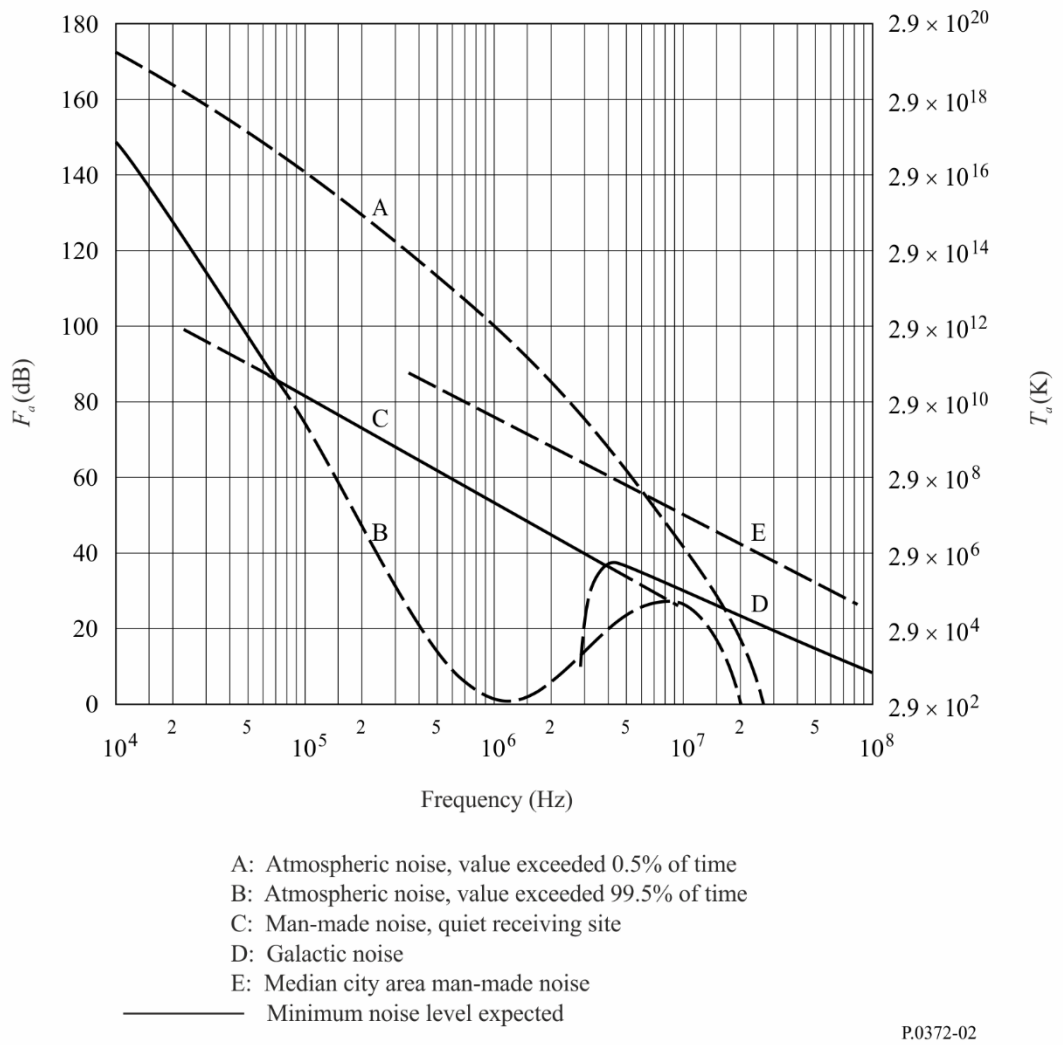
6.7.2 Sources of radio noise

According to Recommendation ITU-R P.372 the three main sources of radio noise are atmospheric, galactic and man-made noise (MMN). The level of external noise is given as a noise figure F_a. It is the total RF power delivered from an ideal isotropic antenna above the thermal noise power (kT_0b).

Figure 6-129 (Recommendation ITU-R P.372-17, Figure 2) provides an estimate of the noise levels over the frequency range of 10^4 to 10^8 Hz, i.e. 10 kHz to 100 MHz, for various categories of noise.

FIGURE 6-129

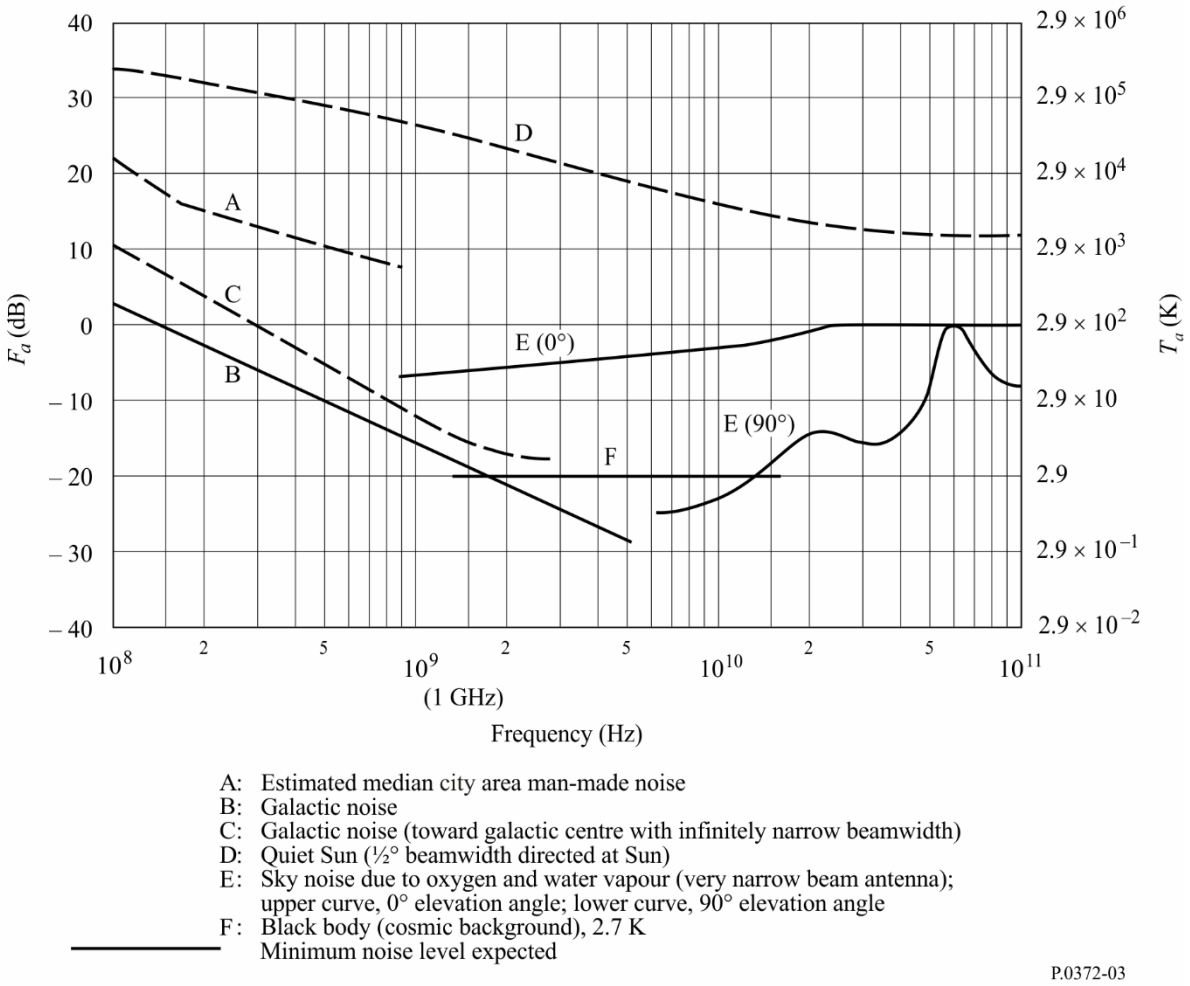
Radio Noise from 10 kHz to 100 MHz



The noise levels over the frequency range 100 MHz to 100 GHz are given in Fig. 6-130 (Recommendation ITU-R P.372-17, Figure 3).

FIGURE 6-130

Radio Noise from 100 MHz to 100 GHz



It can be seen that depending on frequency, different sources of radio noise are dominant. Table 6-29 contains the dominant sources for the most relevant frequency ranges up to 1 GHz.

TABLE 6-29

Importance of radio noise sources per frequency range

Noise source	Frequency range of importance
Atmospheric noise	below 100 kHz
Galactic noise	3 MHz to 100 MHz
Man-made noise	9 kHz to 1 GHz[17]

[17] Indoor measurements indicate that MMN is present up to 2 GHz (see details at: https://www.ofcom.org.uk/spectrum/innovative-use-of-spectrum/update-on-ofcoms-long-term-radio-noise-monitoring-campaign and https://ieeexplore.ieee.org/document/11361568).

While the first two sources do not change significantly over time, the effect and impact of MMN can vary with the density and activity of electrical and electronic devices, so this is the part that is mainly of interest when performing radio noise measurements.

When assessing the impact of radio noise on communication services, antennas using the preferred direction of those services should be used because then the main source of measured radio noise will be man-made noise.

6.7.3 Components of radio noise

In Recommendation ITU-R P.372, the terms "radio noise", "radio-frequency noise" and "RF noise" are synonymous. Radio noise in an environment originates from multiple sources including electrical and electronics equipment and spurious emissions from communication systems. If at a given measurement location there is no dominance of single noise sources, the distribution of the MMN approaches additive white Gaussian noise (WGN).

However, with the high density of noise emitting devices especially found in cities, residential areas and indoors, it is virtually impossible to find a location that is not at least temporarily dominated by noise or emissions from single sources.

These sources often also emit impulse noise (IN) or Single Carrier Noise (SCN). Since radiocommunication equipment has to operate in such an environment, it is unrealistic to exclude these components from radio noise measurements. Recommendation ITU-R P.372 states 'For impulsive noise processes at the higher frequencies (i.e. > about 1 GHz), F_a values are quite low and only the higher magnitude pulses appear above the receiver's noise threshold. Impulsive noise can be described by its peak value for a given time period, exceedance probabilities at these higher levels, and the pulse count at a specified level.

Single Carrier Noise is only detected as such when it comes from a single source nearby the measurement location. Multiple sources emitting single carriers quickly add up to a noise-like spectrum as their numbers increase.

Radio noise can be a combination of WGN, SCN and IN. The noise levels vary with frequency, proximity to noise sources and device activity. Noise levels tend to decrease at higher frequencies and greater distances, but increase with the number of noise sources.

TABLE 6-30

Components of radio noise

Noise component	Properties	Sources (examples)
White Gaussian Noise (WGN)	Uncorrelated electromagnetic vectors. Bandwidth equal to or greater than receiver bandwidth. Spectral power level increases linear with bandwidth.	Computers, power line communication, ultra-wideband devices, wired computer networks, galactic noise, LED.
Impulse noise (IN)	Correlated electromagnetic vectors. Bandwidth greater than receiver bandwidth. Spectral power level rises with square of bandwidth.	Ignition sparks, lightning (atmospheric noise), gas lamp starters, computers.
Single Carrier Noise (SCN)	One or more distinct spectral lines. Bandwidth smaller than receiver bandwidth. Spectral power level independent of bandwidth.	Wired computer networks, computers, switched mode power supplies, wireless power transfer, active TV antennas

6.7.4 Key parameters

While the WGN component is sufficiently characterized by the RMS level value, other metrics also need to be considered for characterizing Impulse Noise. Modern digital communication services almost always apply error correction, making it more immune especially against impulse noise. However, when certain pulse lengths and repetition ratios are reached, IN can significantly interfere with the operation of such a service. It is therefore desirable to measure radio noise in a way that gives not only the level of IN but also information about the statistical distribution of pulse parameters like pulse duration and repetition frequency.

6.7.5 Measurement types

Recommendations ITU-R SM.1753 and ITU-R SM.2093 provide details of radio noise measurement procedures. The recommendations identify the following three possible types for radio noise measurements:

Type A: WGN only. This methodology delivers only WGN levels, disregarding IN. It only requires measurements of the remaining RMS level on a "free" frequency. Evaluation of data is simplified. Standard monitoring equipment can be used in most cases.

Type B: WGN and IN. This methodology delivers WGN levels and characteristics of the important IN parameters of radio noise. It requires measurement equipment capable of sampling the momentary signal level at a very fast speed. Data evaluation is more complex and requires extensive post- processing, most of which can only be performed by computers.

Type C: WGN, IN and separation of MMN. In addition to WGN level and IN characteristics, this methodology separates atmospheric impulse noise from MMN to a large extent, which may be important in the HF frequency range and below. The measurement process is similar to B), but it has to be performed at two different locations and the equipment of both locations has to be exactly time synchronized.

6.7.6 Measurement locations and frequencies

Even on one frequency the radio noise level, especially when dominated by MMN, depends on time, location and propagation conditions, etc. A statistically relevant figure for the noise level can only be derived by averaging results from multiple measurements at different but similar locations. Measurement environments can be categorized based on the density, proximity and type of noise sources. In indoor environments, the physical dimensions on the building may also impact the level of noise observed.

The practical way to select a proper frequency (band) is to first find a possible candidate band by scanning the desired frequency range and identify the frequency (band) with the lowest signal occupancy or level. The usability of this frequency (band) can be verified by applying the singular value decomposition (SVD) process or with the help of an Amplitude Probability Distribution (APD) plot.

Both methods are described in detail in Recommendation ITU-R SM.1753. If they reveal that the scan contains mostly WGN, the measurement can be used. If not, an alternative frequency (band) can be selected or post-processing of the measurements can help to remove non-noise samples.

Because of the different propagation conditions, different typical bandwidths of communication receivers and different measurement antennas to be used, radio noise measurements may be made separately in the three main frequency ranges of interest, namely:

– LF to HF (9 kHz to 30 MHz).

– VHF (30 MHz to 300 MHz).

– UHF (300 to 3 000 MHz) and above 3 000 MHz.

Recommendation ITU-R P.372 specifies additional noise sources that increase the thermal noise: atmospheric and extra-terrestrial sources. Those and man-made noise cannot be disregarded at frequencies below 1 000 MHz; see Table 6-29.

Recommendation ITU-R SM.1753 provides detailed information on the selection of measurement locations and frequency (bands) for outdoor measurements. For measurements of indoor noise environment, Report ITU-R P.2089 provides detailed information on preferable measurement locations. Report ITU-R SM.2055 describes methods to find suitable frequencies, especially in the HF range.

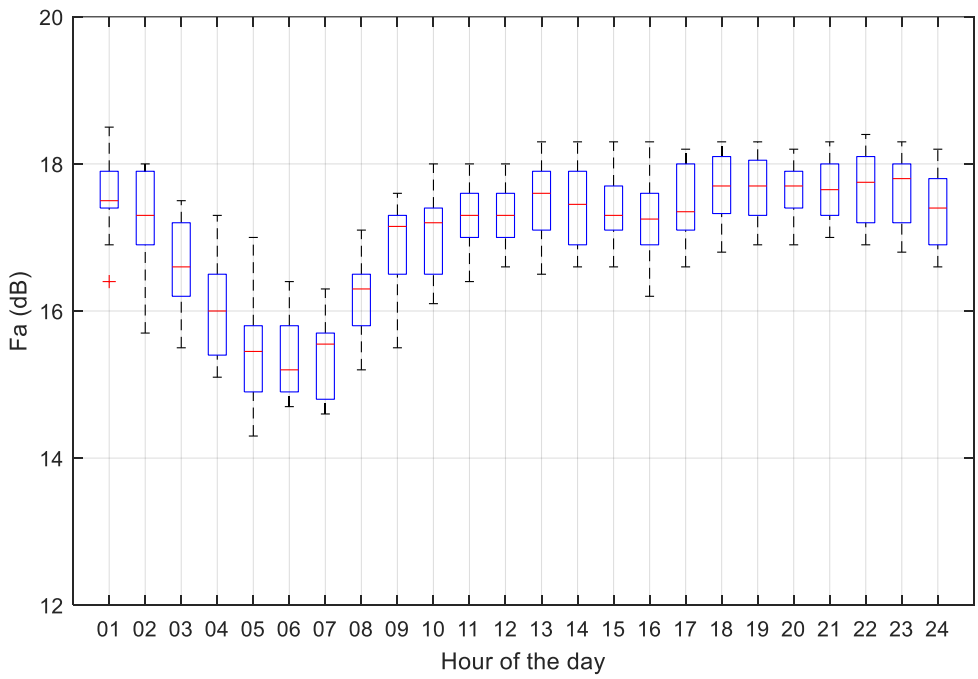
In 2021, the United Kingdom started a long-term radio noise measurement campaign using self-developed measurement systems. Details can also be found in Report ITU-R SM.2055.

6.7.7 Examples of result presentation

A typical presentation of the WGN would be a so-called "box-plot" that indicates the highest, lowest and median values, together with upper 75% and lower 25% of the values like in Fig. 6-131.

FIGURE 6-131

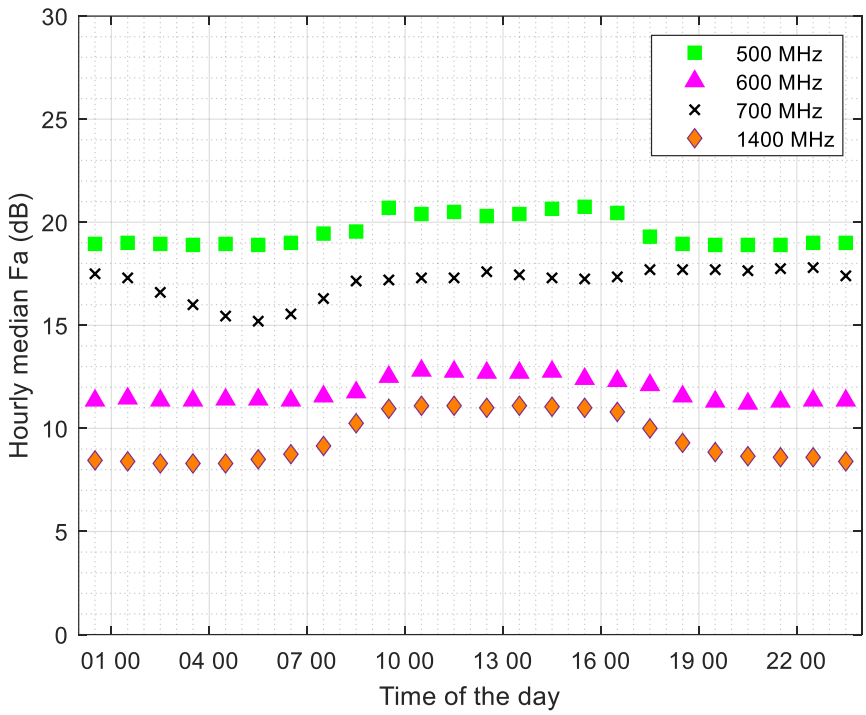
Box plot example



Alternatively, a time series plot of the *Fa* values can be used to visualize and compare the noise levels across different frequency bands in a given location. An example is shown in Fig. 6-132 for measurements in an office environment.

FIGURE 6-132

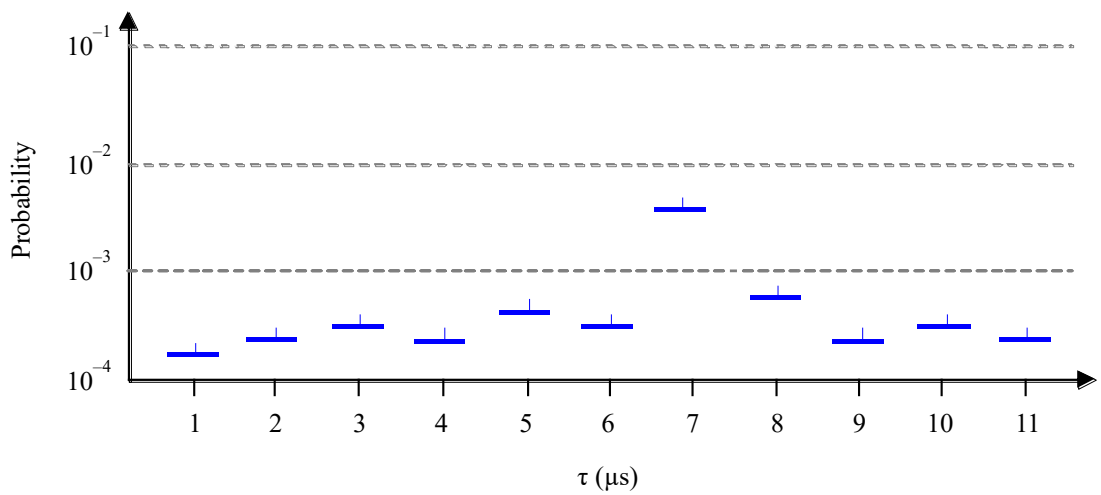
Example of time-series plot of radio noise



Impulse noise parameters can be presented as a probability distribution like in Fig. 6-133 that illustrates the pulse duration.

FIGURE 6-133

Example of impulse/burst length distribution

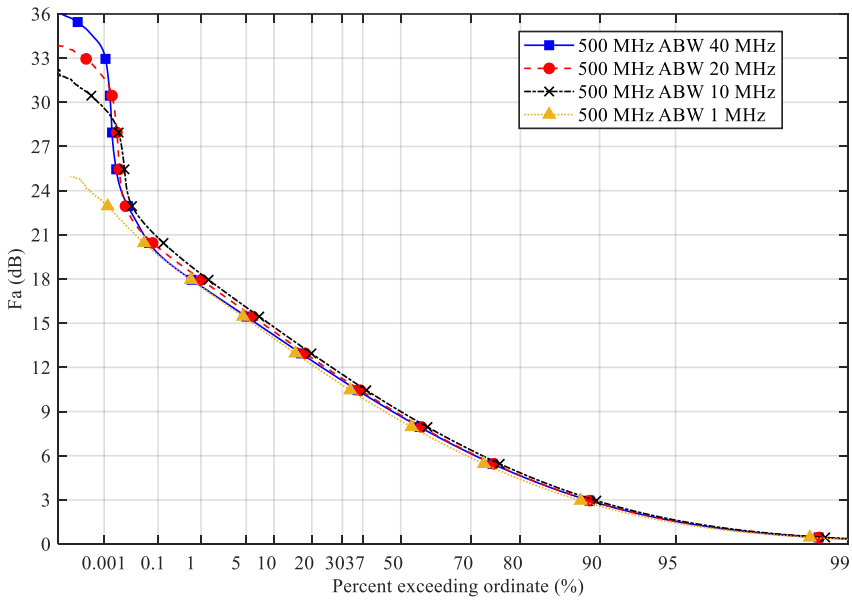


Spectrum-5.7-02

APD plots provide a statistical representation of signal amplitude variations, enabling the differentiation of impulsive noise from WGN and single carrier components, as recommended in Recommendations ITU-R SM.1753 and ITU-R SM.2093. Figure 6-134 illustrates how the IN component is captured by the tail of the derived probability distribution due to its low probability of occurrence and higher amplitude level while WGN levels can be read from the median (37% point) of the APD plot. It should be noted that the system acquisition bandwidth (ABW) impacts the extend of IN components captured, where larger IN levels are typically recorded with larger ABW.

FIGURE 6-134

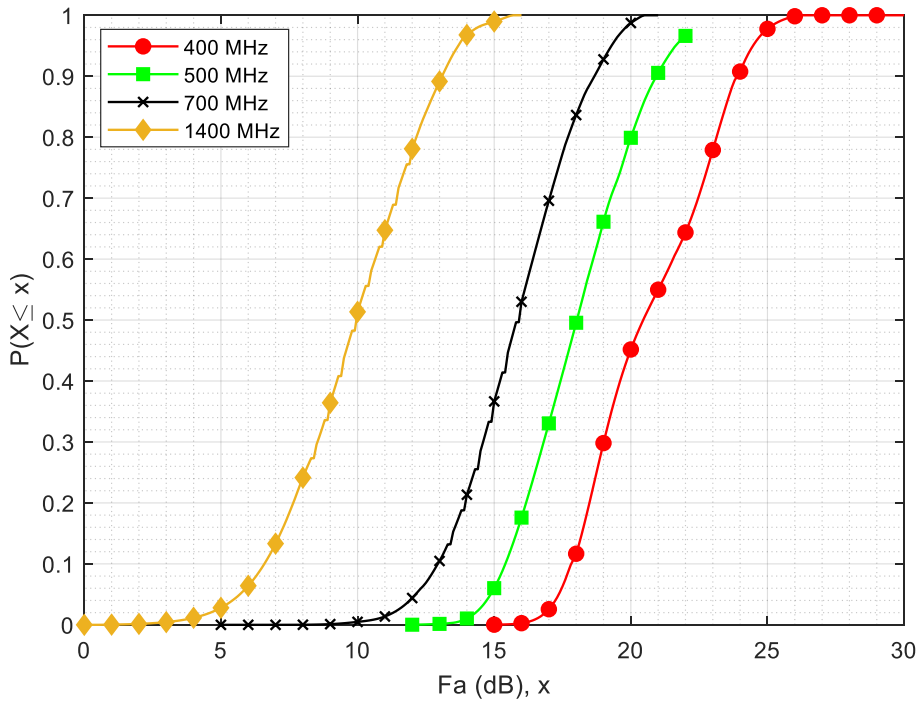
Example of an APD plot



Cumulative Distribution Function (CDF) plots can be supplementary to the APD plots providing a cumulative view of noise levels allowing for the assessment of variability and the identification of dominant noise sources. CDF plots are more suitable for analysing the results of Type A-WGN only measurements. An example is provided in Fig. 6-135.

FIGURE 6-135

Example of CDF of median F_a plot



6.7.8 ITU radio noise databank

Radio noise levels and statistics are most valuable when a large number of registrations can be compiled. For this purpose, the ITU has established a databank where ITU membership can access the available measurement data.

The databank is available at: https://www.itu.int/en/ITU-R/study-groups/rsg3/rwp3l/Pages/RNDB.aspx.

The databank indicates "The measurement method for outdoor radio noise should conform to Recommendation ITU-R SM.1753. The measurement method for indoor man-made noise should conform to Recommendation ITU-R SM.2093. Selection criteria for measurement locations should refer to the definition of location or environmental categories given in those recommendations."

In its first stage the databank contains only WGN levels and only outdoor results. It has since been expanded to include measurement results from a range of indoor environments, broadening its applicability to diverse scenarios.

6.7.9 References

Related ITU-R Recommendations and Reports

NOTE – In every case the latest edition of the ITU-R Recommendation and Report should be used.

Recommendation ITU-R SM.1753 – *Method for measurements of radio noise*

Recommendation ITU-R SM.2093 – *Methods for measurements of indoor radio environment*

Recommendation ITU-R P.372 – *Radio noise*

Report ITU-R P.2089 – *The analysis of radio noise data*

Report ITU-R SM.2055 – *Radio Noise Measurements*

Other document

Update on Ofcom's long-term radio noise monitoring campaign, https://www.ofcom.org.uk/spectrum/innovative-use-of-spectrum/update-on-ofcoms-long-term-radio-noise-monitoring-campaign and https://ieeexplore.ieee.org/document/11361568.

6.7.10 Abbreviations/Glossary

APD	Amplitude probability distribution
F_a	Noise figure (external noise power above thermal noise in dB as in Recommendation ITU-R P.372)
IN	Impulse noise
MMN	Man-made noise
SCN	Single carrier noise
WGN	White Gaussian noise

CHAPTER 7

Fundamentals and supporting tools

TABLE OF CONTENTS

Page

7.1 Radio Navigation Satellite Service (RNSS) 628

7.1.1 General 628

Bibliography 629

7.2 Maps 629

7.2.1 Use of Geographic Information Systems (GIS) 629

7.2.2 Sources of digital data 630

7.2.3 Types of digital map data 633

7.2.4 Map resolutions for radio-wave propagation prediction calculations 636

7.2.5 Geographic coordinate systems 637

References 638

Bibliography 639

7.3 Radiated power calculations 639

7.3.1 Introduction, e.r.p. and e.i.r.p. definition 639

7.3.2 Estimation of the e.i.r.p. using received power measurements 640

7.3.3 Total radiated power definition 642

7.3.4 Estimation of the TRP by field strength measurements 643

7.3.5 Propagation influence 644

References 644

7.4 Propagation models 644

7.4.1 Effects of the atmosphere 644

7.4.2 Effects of obstacles and irregular terrain 645

7.4.3 Effects of reflections by the surface of the Earth 646

7.4.4 Propagation on Earth-space paths 646

7.4.5 Available propagation models 646

7.4.6 Propagation models and usage of various frequency bands 647

References 648

7.5 Intermodulation 649

7.5.1 Background 649

Page

7.5.2 Intermodulation analysis equations 649

7.5.3 Detection and identification of intermodulation products 651

Bibliography 652

7.6 Modulation and spectrum access methods 652

7.6.1 Introduction 652

7.6.2 Analogue modulation 652

7.6.3 Digital modulation 660

7.6.4 Spectrum access methods 666

Bibliography 676

7.7 Fast Fourier transform 676

7.7.1 Basics 676

7.7.2 Analogue to digital conversion, sampling 678

7.7.3 Windowing 679

7.7.4 FFT implementations, overlap processing 681

7.7.5 Range of applications 683

Bibliography 683

7.8 Planning and optimization of spectrum monitoring networks 684

7.8.1 Introduction 684

7.8.2 Principles for the planning and optimization of spectrum monitoring networks 684

References 687

7.9 Measurement uncertainty 687

7.9.1 Introduction 687

7.9.2 Overview and definition of measurement uncertainty 688

7.9.3 Common distribution functions to express uncertainty 688

7.9.4 Application 690

7.9.5 Example of an uncertainty calculation 691

7.9.6 References 694

7.10 Antenna processing and spatial diversity 694

7.10.1 Introduction 694

7.10.2 Antenna processing for spectrum monitoring 695

7.10.3 Antenna processing principles 696

7.11 Required documentation 697

7.11.1 Basic and general international documents 698

Page

7.11.2 Minimum documentation that should be available at monitoring stations 698

7.11.3 ITU-R Recommendations 699

7.11.4 Radiocommunication SG 1 Recommendations and Reports 699

7.11.5 ITU-R Handbooks 700

7.11.6 Relevant ITU-R software 701

7.11.7 Internet websites 701

7.1 Radio Navigation Satellite Service (RNSS)

7.1.1 General

The Global Navigation Satellite System (GNSS) is one application in the Radio Navigation Satellite Service. There are other applications such as regional navigation services, but this Handbook mainly concentrates on GNSS.

7.1.1.1 Purpose

GNSS are essential for monitoring purposes such as:

Positioning:

– *Licensing*: verification of the position of the stations as stated in the licence, determination of the position of illicit stations.

– *Mobile DF systems*: prediction of the exact position of mobile DF systems.

– *Mobile field strength, power and power density measurements*: location of coverage measurements of transmitters and radio networks; verification of location of maximum field strength for safety reasons.

– *Measurement of antenna patterns*: helicopter or drone-based antenna patterns measurement.

Timing and frequency standard:

– *Time*: synchronization of DF networks in case of very short duration signals; synchronization of time references on monitoring receivers used for TDOA measurements

– *Frequency*: providing a stable frequency reference to monitoring receiver local oscillators.

The GNSS have also capability to predict velocity and direction, but not all are accurate enough for the monitoring requirements.

Given line of sight ("in view") to four GNSS, these services provide positioning globally, continuously and under all weather conditions to users at or near the surface of the Earth. Receivers operate passively, thus allowing an unlimited number of simultaneous users. The GNSS have features which can deny accurate service to unauthorized users.

The ranging codes broadcast by the satellites enables the receiver to measure the transit time of the signals and thereby determine the range between the satellites and the user. Four satellites are normally required to be simultaneously "in view" of the terrestrial receiver for three-dimensional (3-D) positioning purposes. Maritime receivers may need only three satellites as the altitude above mean sea level is approximately 0 metres.

Recommendation ITU-R M.1787 provides information on orbital parameters, navigation signals and technical characteristics of systems and networks in the RNSS (space-to-Earth, space-to-space) operating in the bands 1 164-1 215 MHz, 1 215-1 300 MHz and 1 559-1 610 MHz.

Recommendation ITU-R TF.767 describes the use of GNSS in those applications requiring global coverage and time accuracy levels of about 10-100 ns. Local rubidium or caesium standards can also provide frequency and time references for all the monitoring equipment.

The use of the GNSS has become the default standard for global positioning where accuracies within 20 m are sufficient. Once initiated, the system can provide updated positioning information approximately every 1 s (this interval can be adjusted upon user's preference). In a mobile vehicle, this typically provides enough accuracy to determine which side of the street you are on and is usually sufficient for performing coverage measurements of large cells or broadcast systems.

ITU Radio Regulations (RR) Article **5** details the frequency allocations from 1 215 to 1 626.5 MHz assigned to the radionavigation-satellite service (RNSS) on a primary basis.

Using multiple GNSS systems for user positioning increases the number of visible satellites, improves precise point positioning (PPP) and shortens the average convergence time.

7.1.1.3 Available equipment

Many commercial receivers provide additional outputs derived from the satellite data, including elevation, velocity, and acceleration. Options for waypoint navigation are also available from several manufacturers. In mobile systems which include a computer workstation, stand-alone receivers are often equipped with a data interface enabling GNSS information to be integrated with computerized maps (see § 5.7.3.3) and providing real-time display of a vehicle's position while in motion.

Accuracy and signal capture can be problems when using GNSS in mobile applications. Much higher accuracy positioning is required when measuring micro-cells in building areas and areas for pedestrian traffic. Signal capture from the satellites is problematic in urban areas, inside buildings, and other areas where substantial obstructions may obscure reception. In these cases, it becomes necessary to use an alternative positioning technique.

7.1.1.4 Improvement in accuracy

Accuracy of GNSS can be improved by combining systems such as altimeters, inertial navigation systems as well as techniques provided by the system itself, such as differential GPS (DGPS) for GPS, GLONASS, GPS+GLONASS. Some recent modifications in accuracy are telemetry functions, SBAS, MSAS, augmentation satellite system, QZSS, SDCM.

Bibliography

ITU-R Publications

Final Acts of the WRC-23

Recommendation ITU-R M.1787 – *Description of systems and networks in the radionavigation-satellite service (space-to-Earth and space-to-space) and technical characteristics of transmitting space stations operating in the bands 1 164-1 215 MHz, 1 215 1 300 MHz and 1 559-1 610 MHz*

Recommendation ITU-R TF.767 – *Use of global navigation satellite system for high-accuracy time transfer*

Recommendation ITU-R S.1713 – *Methodology to calculate the minimum separation angle at the Earth's surface between a non-geostationary HEO-type FSS satellite in its "active" arc and a geostationary satellite*

Recommendation ITU-R S.1758 – *Characterization of HEO-type systems in the fixed-satellite service*

NOTE – In every case, the latest edition of the Recommendation is encouraged to be used.

Other Publications

ITU and Wiley, *Satellite Communications (FSS)* https://www.itu.int/pub/R-HDB-42

7.2 Maps

7.2.1 Use of Geographic Information Systems (GIS)

Geographic Information Systems (GIS) serve as one of the essential components of computer-based automated spectrum monitoring systems, whether operating in stand-alone mode or integrated into broader spectrum management frameworks.

The importance of digital GIS cannot be overstated: it offers efficient, dynamic, and interactive means of visualizing and managing geographical data along with the visual representation of objects relevant to spectrum monitoring activities, such as: sites of known transmitters from the spectrum management database, locations of fixed monitoring stations, mobile measurement sites, and estimated locations of unknown transmitting stations derived from direction finder or TDOA measurements.

Maps tailored to various needs may be used to add context and information to spectrum management and monitoring data, whether it is an administrative map to determine the location of an object within a district or country, or road and street maps to verify that measurements were taken along a specified route or within a city.

Through the digital map representation of various objects, measurements and predictions, the user can have quick access to critical properties, such as technical and administrative details of radio stations.

Another essential aspect of automated spectrum management and monitoring systems is the prediction of field strength for transmitting stations, which relies on appropriate radio-wave propagation prediction models.

For accurate predictions, access to various types of geographical data, such as topographic and land-use data is required. Sometimes, additional data types may also be necessary to ensure precise calculations. These geographical data are usually organized as multiple map layers within the GIS. Therefore, digital mapping serves as a foundation for most radio-wave propagation simulations (see § 7.4).

Creating precise terrain elevation and land use data is costly and resource intensive. Furthermore, as higher spatial resolution is required, not only costs are increased, but also such data becomes more susceptible to be affected by human activities, thus resulting in shorter usable life expectancy for the acquired GIS data.

Fortunately, there are several open map data sources that are available and may be used with significant reduction to the costs associated with the use of GIS solutions within spectrum monitoring activities. This section makes use of some of these mapping data sources as examples to various applications.

While radio-wave propagation calculations provide an estimation of emission scenarios over extended periods, they play a critical role in coverage simulations and in the identification and the analysis of measurements. Accurate field strength measurements and emitter location are crucial for ensuring that transmitting stations comply with their licensing conditions.

Radio-wave propagation prediction calculations strongly depend on the quality of their input data. A key factor in such calculations is the resolution of the map layers used. There is a direct relationship between layer resolution and parameters such as transmitting frequency and power. Generally, higher resolution data are required as frequency increases.

The necessary resolution is also relative to the nature of the environment: for areas with rapidly varying relief, such as in mountainous regions, finer resolution (high-resolution) is required to properly represent the terrain. Other influencing factors include the type of radio service, the elevation of the transmitting and receiving antennas, and the specific geographical area of interest.

Finally, the availability and cost of digital data will increase with the required resolution and may also increase the costs associated with the required hardware and software.

7.2.2 Sources of digital data

In this section, several data sources are mentioned as examples. The selection of such examples considered the following characteristics:

Availability: Mentioned data sources must not be protected by copyright or classified by governmental or military authorities. With the rise of open-data initiatives, many high-quality datasets such as Copernicus DEM and NASADEM are freely available.

Quality and density of information: Although mentioned examples of data sources may not always match the user's specific needs, preference was given to those that are more complete, in terms of the information contained or the area included.

Up-to-date information: In many countries and for several data source types, the interval between updates may be exceedingly long, which impacts the reliability of land use datasets. Current satellite missions like NASADEM, TanDEM-X, and the Copernicus DEM are also updated more frequently.

7.2.2.1 Existing digital maps

The first place to look for digital map data sources is the internet. Over the years, many initiatives produced a large volume of data that can now be freely accessed and provide most of the needed information to support spectrum monitoring activities. This includes many governmental agencies that are responsible for maintaining the data or collected the data and made it available as part of open data policies to promote and incentivize development of the digital economy.

Digital topographic data are available in many formats from various sources and may be freely used. Most notable examples are datasets such as: NASADEM Merged DEM Global 1 arc second [NASADEM], Copernicus DEM - Global and European Digital Elevation Model [Copernicus DEM], and the ALOS Global Digital Surface Model [AW3D30].

Some of these sources provide data with spatial resolution as high as 30 m for most of the world land areas, and even reaching 10 m for certain regions, making them valuable for most applications related to spectrum monitoring.

Common sources for the generation of digital geographic data are satellite images and aerial photography. Advancements in remote sensing technologies, such as LiDAR (Light Detection and Ranging) and interferometric SAR (Synthetic Aperture Radar), enabled more automated and accurate generation of digital terrain models (DTMs) and derived products such as ground cover/land-use datasets e.g. high-resolution satellite missions such as TanDEM-X [TanDEM-X] and Copernicus DEM.

High resolution data may be demanding on processing requirements without producing a corresponding increase in the quality of obtained results. To circumvent such limitation, it is common to reprocess the high-resolution data into lower resolution using open-source solutions such as Geospatial Data Abstraction Library (GDAL).

Most countries also have a government entity responsible for maintaining geographical information, such as political borders and population census data. This geographical information may also be obtained and integrated into the spectrum management and monitoring solutions to provide added information and value, for example, estimation of the population with access to a service or affected by an interference. Other non-governmental maps are available and may be useful for spectrum monitoring.

7.2.2.2 Paper (printed) maps

Elevation, land-use, and associated features along with linear elements (e.g. roads, rivers) can be extracted from conventional paper maps by scanning the maps and then converting the raster data into vector format that numerically describes the original map features. To produce a raster DTM, further interpolation of the vector data corresponding to the elevation contour lines needs to be performed.

While the digitization process using paper maps is still a viable method for medium-accuracy geographic data, the advent of satellite imagery, LiDAR, and other advanced technologies led to higher-accuracy, automated methods for producing geospatial datasets in modern contexts.

Historically, map scanning was one of the cheapest and fastest methods to produce large-scale geographic databases, particularly for regions in which 1:200 000-scale maps or larger were widely available and could be processed with relative ease. The data derived from such maps was typically sufficient for many operational and analytical applications, though it might lack the precision available from newer technologies.

When working with older paper maps, accuracy is primarily dependent on the scale that determines the level of detail. The resolution of the map can be estimated by considering that 1 mm on the map represents the smallest discernible feature at that scale. For example, a 1:50 000 scale map corresponds to about 50 m actual, and a 1:250 000 scale map corresponds to a real resolution of about 250 m.

Accuracy in XY-direction is mostly determined by the thickness of the contour lines, while the Z resolution (elevation) depends on the density of contour lines in the area and the terrain type.

Table 7-1 compares the achievable accuracy using modern data sources:

TABLE 7-1

Typical achievable accuracy from different map scales (modern datasets)

Map scale	XY (m)	Z – Flat area (m)	Z – Mountainous area (m)
1:25 000	1-5	0.1-0.5	1-5
1:50 000	5-10	0.5-2	3-10
1:100 000	10-20	1-3	5-20
1:200 000	20-40	3-5	10-30
1:250 000	40-50	5-10	15-40
1:500 000	50-100	10-20	30-100

7.2.2.3 Optical and infrared satellite imagery, aerial photography and laser scanning

Optical Earth observation satellites carry passive instruments designed to measure the brightness, or radiometry, of the Earth's surface across various "optical" wavelengths. Such satellites are characterized by their orbit and imaging instruments, which together define the resolution of the system. Most Earth observation satellites are placed in a sun-synchronous orbit at an altitude of 800 km, enabling them to capture daylight imagery from most of Earth's surface (cloud cover permitting). These satellites can cover several thousands of km^2 in a single pass and revisit any specific location at regular intervals.

Optical sensors onboard satellites cannot penetrate cloud cover, haze, or mist, which restrict their effectiveness in such weather conditions. On the other hand, synthetic aperture radar (SAR) satellites can penetrate most weather conditions, including clouds, rain, and smoke, making them ideal for all-weather, day-and-night Earth observation.

Several satellites with optical sensors onboard are currently available, as summarized in Table 7-2.

TABLE 7-2

List of previous and current satellites with optical sensors

Satellite	Owner	Sensor	Resolution (2) (m)	Image size (km)	Open data
Landsat (1)	Space Imaging Corporation	TM	30 (MS)	185	Y
Landsat-7 (1)	Space Imaging Corporation	ETM	30 (MS) 15 (PAN)	185	Y
		HRMSI	10 (MS) 5 (PAN)	60	Y
Landsat-8/9	NASA/USGS	OLI	30 (MS) 15 (PAN)	185	Y
Sentinel-2A/B	ESA (Copernicus)	MSI	10 (MS)	290	Y
SPOT[1]	CNES (Centre National d'Etudes Spatiales)	HRV	20 (MS), 10 (PAN)	60	N
SPOT 6/7 (1)	Airbus Defence and Space	NAOMI	1.5 (PAN), 6 (MS)	60	N
Pleiades Neo	Airbus Defence and Space	NAOMI NEO	0.30 m (PAN), 1.2 m (MS)	14	N
JERS-1 (1)	Japan Aerospace Exploration Agency (JAXA)	ADEOS	16 (MS) 8 (PAN)	75	Y
IRS-1C	Indian Space Research Organisation (ISRO)	LISS-III	23 (MS) 5.8 (PAN)	70	Y

(1) Decommissioned.

(2) Sample of satellites in orbit (MS – Multi spectral sensor; PAN – Pan chromatic sensor).

Aerial photography plays a significant role in generating high-resolution DEM datasets. It is particularly useful in cases where satellite-borne sensors cannot meet the resolution and accuracy requirements for civil applications. Aerial photographs are typically captured at scales ranging from 1:10 000 to 1:30 000, with generous overlap between adjacent frames. This overlap allows for the creation of stereo pairs, which can be digitized using precision scanners to produce digital images with resolutions between a few decimetres and 1 or 2 m.

Such high-resolution images can be processed using digital workflows to create a variety of products, including orthophotos, DTMs, DEMs, building models, land-use maps and vector data. However, one of the main drawbacks of aerial photography is its limited availability. Up-to-date aerial photographs may not exist for many regions of interest, and even when available, they are often classified or confidential. Furthermore, due to the small area covered by each frame, users often need to purchase and process numerous photos, which can significantly increase project costs.

Laser scanning LiDAR is an advanced technique for creating DEMs with a high degree of automation. The laser scanning system is typically airplane-based and incorporates a differential GPS system as well as an inertial measurement unit, to measure the acceleration and change of orientation of the sensor platform. These systems track the airplane's trajectory with an accuracy of about 2 cm, while the laser system measures the distance to the Earth's surface with an accuracy of 1 cm. The laser beams are reflected from the surface, providing precise distance measurements, which are then used to create highly accurate 3D terrain models.

In summary, Table 7-3 provides an overview of the various data sources and their achievable horizontal resolution.

TABLE 7-3

Overview of various data sources

Data Source	Data Type	Achievable Resolution (m)
Paper maps Scale: 1:20 000 – 1:500 000	Road map	2-100
	Digital terrain model, clutter	10-200
Satellite imagery	Image	1-50
	Digital elevation model, clutter	5-50
Aerial photography	Photo	0.1-5
	Digital elevation model, buildings, clutter	0.5-5
Laser scanning	Photo	0.1-5
	Digital elevation model, buildings, clutter	0.5-5

7.2.3 Types of digital map data

Depending on the application, distinct types of map data may be required, such as:

– geographical maps, road maps, and geo-referenced photos,

– digital terrain model (DTM),

– digital elevation model (DEM),

– clutter data,

– building height data,

– radio-meteorological data (e.g. atmospheric radio refractivity maps, radio climatic zones),

– ground conductivity data.

Such data have to be geo-referenced using a suitable coordinate system and datum before they can be used as digital maps in a GIS.

Most GIS solutions include multi-layer and transparency controls to allow the visualization of overlapping features including those obtained from external data sources and those maintained and produced by administrations, such as known e geolocated electromagnetic field emissions sources and results from radio-wave propagation prediction calculations.

Suitable GIS software can also facilitate manipulating and producing digitized maps to be used by the management and monitoring system in its various activities.

GIS data formats can be classified into two data types:

– *Vector data (Line data)*: The geographical information is stored in polygons that follow linear features (roads, railways, contour lines, etc.) or surround areas of the same feature (political boundaries, lakes, city contours, forest contours). Additional information (e.g. number of inhabitants, income, inhabitants by age, names of streets or cities) can be attached to the geographical elements that identify the area to which the information is associated. Vector data usually are less voluminous than raster data and allow for infinite zoom in, and easy modification of the visual characteristics, allowing better use of accessibility features. On the other hand, it may be more time-consuming to obtain and maintain the data, e.g. identification of objects associated with human activities, such as store names and activities, may change in a short time period, without notification.

– *Raster data (Gridded data)*: The area is divided into equally spaced rectangles of a certain size that may be defined in distance, more common, or in degrees of longitude and latitude. The size of these rectangles is called spatial resolution. For each of these rectangles, one element of information is stored, e.g. the terrain height, the clutter class, the number of inhabitants living in this rectangular area or simply graphical information of a photo or a scanned paper map. Raster data is more suitable to images and their derived data, such as DEM, allowing for fast access to each raster point and reducing the need of numerical interpolations.

Common data exchange formats for vector and raster data files are listed in Table 7-4.

TABLE 7-4

Common data exchange formats for vector and raster data files

Data type	Common file formats
Vector data	AutoCAD DXF / DWG, Esri ArcInfo E00, Esri ArcView Shape, MapInfo TAB, MapInfo MIF / MID (ASCII Export Format), Microstation DGN, SDTS, TIGER, VPF
Raster data – Image formats	BMP, GIF, JPG, TIFF, GeoTIFF
Raster data – Terrain data formats	ASCII Grid, ASCII XY Value, BIL, BIP, BSQ, DTED, ESRI Generic Binary, Planet

A GeoPackage (.gpkg) can store both vector and raster data, making it a versatile, open, standards-based format for geospatial information.

7.2.3.1 Administrative maps, road maps and geo-referenced photos

Administrative maps and road maps can be used to display site positions, coverage areas, and the direction of beams toward transmitters or monitoring stations. Administrative maps are useful to indicate the location of a transmitter and monitoring stations in a larger area. Maps in different resolutions can help to identify the locations of known and unknown transmitter stations and the relative position of known natural and manmade features. Aerial photos or satellite images provide an up-to-date view of the area of interest and can additionally identify areas where reflection of radio signals might occur or the location of objects acting as obstacles to propagating radio-waves.

7.2.3.2 Digital terrain model

A digital terrain model (DTM) represents the bare Earth's surface in raster or vector format, supplying the altitude of each point above mean sea level (AMSL) of the represented area. The height of buildings, trees, or other land use above the Earth's surface is not part of the DTM.

The resolution of a DTM is given by the resolution in ground plane (XY-direction corresponding to longitude and latitude) and the resolution of the point altitude. As specified before, the required resolution is derived from the range of operation, the area of interest, the services under examination, and the radio-wave propagation prediction models used.

Map resolutions can vary from the kilometre range to a few centimetres and may be different in each of the three directions. Figure 7-1 depicts a schematic of a profile of a digital terrain map without buildings, trees, etc.

7.2.3.3 Building data and digital elevation model

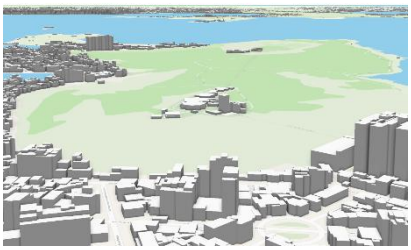
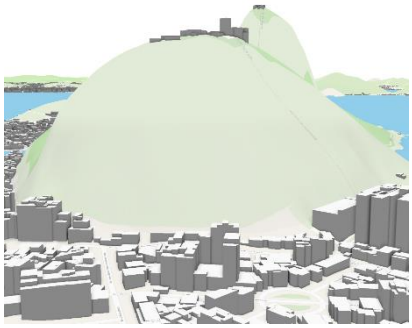
Buildings typically add to the altitude of the Earth's surface acting as an additional obstacle to propagating radio waves. Building data are often used to verify line-of-sight conditions for microwave-link and point-to-multipoint (P-MP) planning. Typical resolutions are in the range of few meters or even less than one meter since the data should not be coarser than the size of the objects represented.

Building data are stored in raster or vector format. The vector format is preferred for 3D simulations of urban areas. For a given resolution, compared to raster data, vector data can include more details such as specific building shapes. This information needs more regular updates, compared to DTM datasets, as buildings and their heights are changing more often than the ground level above sea.

A DEM shows the elevation of the surface of the Earth plus land use, including the building height. DEMs are used for microcell, microwave-link and P-MP planning purposes, whereas GIS tools can verify line-of-sight conditions and field strength calculations can be performed. Figure 7-1 depicts a DEM profile with building data: the surface of the Earth plus building heights.

FIGURE 7-1

DTM, building height and DEM profiles

(a) DTM profile	(b) Building height profile	(c) DEM profile
		

7.2.3.4 Clutter data

Clutter data, also called land use, morpho, land coverage, or ground occupancy data, contains classification information of the clutter items (ITU-R classification), including bare mineral surface, field or cultivated land, forest, water, dense urban area, diffuse urban area, or mixed urban area.

This information could be supplied as vectors (by supplying polygon surfaces of points of the same class: e.g. lake, forest, and city contour) but the raster format is more convenient to be used by radio-wave propagation prediction models. In the latter case, the clutter data map represents either qualitative data as to which item (e.g. urban, suburban, forest and water) exists at each pixel, or rather quantitative values such as the vegetation density or building density or height.

Radio-wave propagation prediction models can use clutter data maps to determine the additional attenuation that such obstacles impose upon propagating radio waves. Some field strength prediction models such as Recommendations ITU-R P.452, ITU-R P.1812, ITU-R P.2001, Okumura-Hata and Walfish Ikegami require clutter data in addition to DTM's to improve the precision of the predictions.

Typical resolutions of clutter data maps will vary according to the requirements to properly depict features but are also commonly derived from image data and thus present the same spatial resolution seen in DEM and DTM data.

7.2.3.5 ITU Digitized World Map

The ITU Digitized World Map (IDWM) was developed to integrate necessary geographical, political, radio-meteorological, and technical data and can be used in a wide range of calculation tasks.

The IDWM database contains the following data: geographical data (such as coastlines, seas, islands, and lakes), geopolitical data (such as country and region borders), radio-meteorological data for rain climatic zones and technical data such as ground conductivity areas and noise zones.

In addition, the IDWM provides a subroutine library offering functions to make full use of the above-mentioned database, such as:

– determination of the region, country, rain climatic zone, etc.

– for a given point, calculation of the distance from a given point to the coast, country border, etc.

– for a given azimuth, calculation of the distance and the azimuth for a given point to the nearest coastline, country border point

– calculation of relevant zones traversed along a profile when a distance calculation is performed and several other functions.

The IDWM is included in most of the software packages offered by the ITU; as example, the ITU bi-weekly BR IFIC depicts the registered stations on a map and the datasets can also be accessed in the BR Geospatial Catalogue.

Readers should be aware of the following IDWM disclaimer: "The designations employed and the presentation of material on maps/infographics do not imply the expression of any opinion whatsoever on the part of ITU and of the Secretariat of the ITU concerning the legal status of the country, territory, city or area or its authorities, or concerning the delimitation of its frontiers or boundaries."

7.2.3.6 Web mapping services

An interesting alternative is the use of Web mapping services, e.g. Open Street Map [OSM] and other online commercial services. They provide world-maps that were created by superimposition of images obtained from satellite imagery, aerial photography and GIS information, e.g. terrain elevation. Most land areas are covered in satellite imagery with a resolution of about 15 m per pixel or even better.

It should be noted that the use of web mapping services may require a licensing contract for government and/or commercial users although their use may be free of charge for private users.

Web mapping may also be provided as an internal service by the administration, using restricted data or a combination of restricted and open data. There are several open-source options that enable the easy deployment of such service.

7.2.4 Map resolutions for radio-wave propagation prediction calculations

The required resolution of all types of map data layers for radio-wave propagation prediction calculations depends on the following parameters:

– terrain;

– emission frequency and power that define the operation range;

– type of service.

The resolution of the map data should be sufficient to consider significant variations of the terrain.

Certain radio-wave propagation prediction models e.g. Recommendation ITU-R P.1812, provide guidance on the most suitable terrain dataset resolution that should be used, noting that a lower resolution might result in averaging or losing terrain detail (obstacles) resulting in an under-estimation of attenuation of the radio-wave, while higher resolutions might result in unnecessary costs for acquisition, maintenance and processing of the data.

The level of detail of variations in the terrain map data required for each propagation model calculation also depends on the wavelength of the emission. As a rule of thumb, details of obstacles smaller than the wavelength do not affect the propagation loss very much, but there are many exceptions to this concept, most notably in areas with large altitude variation, such as valleys and hilly regions. Table 7-5 provides a rough overview of map resolutions required for calculations in the various frequency bands.

Terrain profiles may be extracted from terrain elevation datasets by automatic means referenced to latitude and longitude with respect to a consistent geodetic datum and along the geodesic applicable for that datum, e.g. a great circle in the case of a spherical datum and a geodetic line with zero geodesic curvature for an ellipsoid.

The terrain profile is more important for frequencies above HF (30 MHz); wavelengths smaller than 10 m. For frequencies above 5 to 10 GHz, with no line-of-sight (LoS) between emitter to receiver excess loss due to diffraction is present. In such instances, a DTM with a high resolution and a high accuracy enables a relevant radio-wave propagation prediction model to provide the most reliable results.

TABLE 7-5

Map resolutions for the various frequency ranges

Band	Frequency range	Wavelength (m)	Approximate range of emission (km)	Suggested resolution of map data
VLF	3-30 kHz	100 000-10 000	several 1 000	1 km
LF	30-300 kHz	10 000-1 000	several 1 000	1 km
MF	0.3-3 MHz	1 000-100	few 1 000	1 km
HF	3-30 MHz	100-10	few 1 000	1 km
VHF	30-300 MHz	10-1	up to 1 000	100 m
UHF	0.3-3 GHz	1-0.1	up to 100	~ 10 m
SHF	3-30 GHz	0.1-0.01	up to 30	~ 5 m
EHF	30-300 GHz	0.01-0.001	up to 20	~ 1 m

NOTE – In the above Table, the distance limits and the suggested resolution of map data are applicable to the lower limit of the frequency range indicated in each instance. Suggested resolution of the map considers the size of the features to be represented, and different requirement may be applicable, depending on the specific characteristics of the area represented by the GIS data.

7.2.5 Geographic coordinate systems

Two main types of coordinate systems are used to define maps of interest to spectrum management and monitoring: spherical coordinates and projected (cartesian) coordinates.

Maps portray the spherical Earth's surface on a flat surface. Lines of latitude and longitude are used in the most common coordinate systems, and these are "projected" from the spherical surface to a flat surface using various projections to achieve different results.

A sphere or an ellipsoid approximates the true shape of the Earth. Its form and orientation in space are described by the so-called geodetic datum: the set of reference values upon which a coordinate system is based (see Note 1).

NOTE 1 – The WGS84 datum, which is based on the GRS 80 geoid, is recommended for international coordination. The GRS 80 geoid is an ellipsoid, defined in terms of three values, i.e. its semi-major and semi-minor axes, and its inverse flattening factor. The WGS84 datum was derived from the GRS 80 geoid by adjusting it in terms of the Earth gravitational

model, EGM2008 which describes the Earth's undulation of the equipotential surface owing to the mass distribution of the Earth, see Recommendation ITU-R P.1511.

This transformation is carried out by the map projection. Both, the map projection combined with the datum, form a coordinate system, which fully describes the complete procedure. Diverse ellipsoidal Earth models and various applicable cartographic coordinate systems can be used to define geographical locations on a map. Some projections are particularly suited and accurate only for a limited area of the Earth's surface.

In many cases, the monitoring operator can choose between several map types and different coordinates system presentation (e.g. latitude-longitude in degrees, minutes and seconds or decima degrees) and projection (e.g. Universal Transverse Mercator - UTM, Lambert, Mercator) within the monitoring system.

Most GIS system automatically interchanges/transforms between all the different coordinate types. In some GIS/monitoring systems only one internal reference coordinate system is used, and all other coordinate systems are transformed from and to it. This automatic mechanism allows the operator to use all the different maps without considering their different coordinate systems. However, it is important that the operator should ensure that the coordinate system used for a specific situation is relevant and valid for the selected area of the Earth' surface and the reference datum.

A rectangular coordinate system is frequently used for small areas because of the ease of plotting and calculation (distance separation, for example). In this case, errors from the assumption that the Earth is flat are small. Table 1 of Recommendation ITU-R P.1058 summarizes the differences among coordinate systems.

TABLE 7-6

Geographical coordinate systems

Parameter	Latitude-longitude	UTM	Other
Applicability	Complete Earth	Most of Earth	Usually local
Grid cell shape	Curvilinear trapezoid	Good approximation to square	Usually good approximation to square
Scale-factor variation	Varies with latitude	Good approximation to constant	Usually good approximation to constant
Boundaries	None	According to longitude	Varies

Care should be taken in transferring locations between maps using different coordinate systems. There are several references that present a clear description of these and other important map projections. The following references provide good graphic descriptions and the mathematics necessary for interpretation and conversion. Open-source resources are available for the manipulation of maps and geospatial dataset, and the transformation between coordinate systems, e.g. QGIS and GDAL.

References

GLOBE [2001] 30 arc-second (1 km) gridded quality controlled global DTM is available from NOAA National Data Centres via the Web page: http://www.ngdc.noaa.gov/mgg/topo/globe.html.

NASADEM Merged DEM Global 1 arc second: https://lpdaac.usgs.gov/products/nasadem_hgtv001/

Copernicus DEM – Global and European Digital Elevation Model: https://dataspace.copernicus.eu/explore-data/data-collections/copernicus-contributing-missions/collections-description/COP-DEM

LOS Global Digital Surface Model "ALOS World 3D – 30m (AW3D30)": https://www.eorc.jaxa.jp/ALOS/en/dataset/aw3d30/aw3d30_e.htm

ESAGroundCover: https://esa-worldcover.org/en

TanDEM-X: https://earth.esa.int/eogateway/missions/terrasar-x-and-tandem-x

QGIS: https://qgis.org/

Bibliography

SNYDER, J. P. [1987] Map Projections, A Working Manual. U.S. Geological Survey Professional Paper 1395, United States Government Printing Office, Washington, United States of America.

Institut Géographique National, 135 bis rue de Grenelle, Paris, France, https://www.ign.fr/.

ITU-R Recommendations and Resolutions

Recommendation ITU-R P.1058 – *Digital topographic databases for propagation studies*

Recommendation ITU-R P.1511 – *Topography for Earth-space propagation modelling*

Resolution ITU-R 40 – *Worldwide databases of terrain height and surface features*.

NOTE – In every case, the latest edition of the Recommendation and Resolution is encouraged to be used.

7.3 Radiated power calculations

7.3.1 Introduction, e.r.p. and e.i.r.p. definition

The e.i.r.p. is an important parameter of any emitter and it is needed in determining the operational range, RF interference zone for other receivers, and RF hazards to personnel associated with medical equipment, ordnance, and fuel. It is essential that a monitoring station be able to estimate the e.i.r.p. of an emitter, calculate the power level of the transmitter, compare the measured power to the licence data including the maximum allowable power and antenna gain. The calculation of e.i.r.p. is also essential for the monitoring of spacecraft emissions (see § 6.1.2.4).

According to RR No. **1.161**:

"*equivalent isotropically radiated power (e.i.r.p.):* The product of the power supplied to the antenna and the antenna gain in a given direction relative to an isotropic antenna *(absolute or isotropic gain)*."

The e.i.r.p. can be computed by the following formulae:

$$e.i.r.p. = P_t + G_t - L \qquad \text{dBm} \tag{7-1}$$

where:

P_t : output power of the transmitter (dBm)

G_t : gain of the transmitting antenna, in the direction of the receiver (dB) relative to an isotropic antenna (dBi)

L : transmission line and matching losses (dB).

In the case of an omnidirectional transmitting antenna, the e.i.r.p. is uniform in all directions. For a directional antenna, this value generally depends upon both azimuth and elevation. When e.i.r.p. is stated independent of the direction, the maximum value is implied.

NOTE 1 – A similar term, called e.r.p. (effective radiated power) is often used in the same way. According to RR No. **1.162** definition is as follows:

"*effective radiated power (e.r.p.)* (in a given direction): The product of the power supplied to the antenna and its *gain relative to a half-wave dipole* in a given direction".

It is frequently used in EMC measurements, where an equipment under test (EUT), whose emission has been measured using a calibrated antenna and receiver, is replaced by a half-wave dipole and a signal generator whose output power is adjusted to give the same reading on the measuring receiver display as with the EUT in place. The input power to a lossless half-wave dipole is the e.r.p. to be measured.

Generally, e.r.p. and e.i.r.p. are related by:

$$e.i.r.p. = e.r.p + 2.15 \qquad \text{dBm} \tag{7-2}$$

7.3.2 Estimation of the e.i.r.p. using received power measurements

At a monitoring station, the received power level (P_r (dBm)) can be measured at the input to the receiver. Frequently, the receiver's input impedance is 50 Ω, and the received power is recorded as a voltage V_r (dB(μV)) across 50 Ω.

For input resistance of 50 Ω, P_r and V_r are related by:

$$P_r \text{ (dBm)} = V_r \text{ (dB(μV))} - 107 \tag{7-3}$$

For input resistance of 75 Ω, P_r and V_r are related by:

$$P_r \text{ (dBm)} = V_r \text{ (dB(μV))} - 108.8 \tag{7-4}$$

The e.i.r.p. of the emitter can be estimated from either P_r or V_r as determined at the monitoring site, when the total propagation loss (e.g. from the emitter to the receiver) is known.

7.3.2.1 Calculation of the e.i.r.p. from received power and field strength

The e.i.r.p. of the emitter can be calculated from calibrated received power measurements when the antenna gain, receiving transmission line loss, polarization mismatch loss and propagation loss are known. If the measurement takes place in the maximum gain direction of the emitter antenna:

$$e.i.r.p. = P_r - G_r + R_{loss} + X_{pol} + L_{prop} \tag{7-5}$$

where:

P_r : measured power of the signal at the receiver input (dBm)

G_r : gain of the receiving antenna toward the direction of the monitored Tx (dBi)

R_{loss} : receiving transmission line losses: cable, feed and mismatch losses (dB)

X_{pol} : polarization mismatch (discrimination of transmit and receive antennas) (dB)

L_{prop} : propagation loss (dB).

It is assumed that the receiver bandwidth is greater than the emission bandwidth.

The e.i.r.p. is easily calculated for the case of free-space propagation. The free-space propagation loss, L_{prop}, can be determined by using the following equation:

$$L_{prop} = 20 \log_{10} f + 20 \log_{10} d + 32.45 \qquad \text{dB}$$

where:

d : distance between the transmitter and the receiver (km)

f : frequency (MHz)

and

$$e.i.r.p. = P_r - G_r + R_{loss} + X_{pol} + 20 \log_{10} f + 20 \log_{10} d + 32.45 \qquad \text{dBm} \tag{7-6}$$

These formulas assume free-space propagation and do not include effects such as those due to the ground, obstacles, ducting effects, etc. For other cases, the propagation loss is computed using propagation models; more details in § 7.4.

7.3.2.2 Effect of reflections and obstacles on the determination of e.i.r.p.

Before using the free-space formula, it is necessary to check the path profile to ensure that a free-space path exists. A path may be considered free-space when no terrain extends inside the first Fresnel zone (or, more conservatively, the third Fresnel zone). The formula for the third Fresnel zone radius r (m):

$$r = 30 * \sqrt{\frac{d_1 \, d_2}{f d}} \tag{7-7}$$

where:

d_1: distance from the obstacle to the transmitter (km)

d_2: distance from the obstacle to the receiver (km)

d: total path length (km)

f: frequency (GHz).

To explain the application: for $d_1 = d_2 = d/2$, $d = 10$ km, $f = 2.5$ GHz, the third Fresnel zone radius equals 30 m; e.g. to get a free space loss signal, no building or other obstacle may approach less than 30 m from the middle of the LoS profile. If only the first Fresnel zone radius is required, then only 17.32 m protection is needed.

The first Fresnel zone radius is given by the third Fresnel zone radius divided by 1.732 (= √3).

In order to compute the maximum LoS distance, it is necessary to consider the effects of atmospheric refraction. This normally is accomplished by plotting the path profile using an Earth radius that is larger than the actual radius (6 370 km) by a factor (k). In temperate climates, the median value of k is approximately 4/3. For this case, a relatively simple formula can be used to compute the distance to the horizon (d_{los}) over the sea, or smooth Earth:

$$d_{los} = 4.1 \cdot \left(\sqrt{H_t} + \sqrt{H_r}\right) \qquad \text{km}$$

where:

H_t and H_r are the transmitter and receiver antenna heights (m) above ground level, respectively.

It is possible to relate the field strength to the receiver voltage using an antenna factor. When these quantities are converted to dB:

$$E = V_r + k_e \qquad \text{dB(μV/m)} \tag{7-8}$$

where:

V_r : the measured voltage at the receiver input (dB(μV))

k_e : antenna factor (dB/m) = $-29.77 - G_r + 20\log_{10} f(\text{MHz})$.

Therefore,

$$P_r = E\big(\text{dB(μV/m)}\big) - k_e - 107 \qquad \text{dBm}$$

and the formulae provided above can be used:

$$e.i.r.p. = E - 20\log_{10} f(\text{MHz}) - 77.23 + R_{loss} + X_{pol} + L_{prop} \qquad \text{dBm} \tag{7-9}$$

For free-space propagation:

$$e.i.r.p. = E + R_{loss} + X_{pol} + 20\log_{10} d(\text{km}) - 44.78 \qquad \text{dBm} \tag{7-10}$$

This equation may be derived directly from the well-known expression (see Recommendation ITU-R P.525):

$$E = \frac{\sqrt{30 * e.i.r.p.}}{d} \tag{7-11}$$

where:

E : electric field strength (electric field intensity) (V/m)

e.i.r.p. : equivalent isotropically radiated power (W)

d : distance (m).

Care should be taken that the method to determine the e.i.r.p. by field strength measurements as described here assumes that no reflections are present. In practice, at least the effect of a ground reflection cannot be neglected. The ground reflection, however, could be eliminated by performing a so-called "height scan": The received power is constantly measured while raising the measurement antenna. The linear average of maximum and nearest minimum level is the result that should be used in the formulae above. Section 5.4.6 of Chapter 5 provides detailed guidance on how to determine the field strength of the direct wave impacted by a ground reflection environment.

7.3.3 Total radiated power definition

Total Radiated Power (TRP) is defined as the integral of the power transmitted from all antenna elements in different directions over the entire radiation sphere.

$$TRP = \frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi} P(\theta,\varphi)\sin(\theta)\,d\theta d\varphi \qquad (7\text{-}12)$$

where:

θ : elevation angle in radians

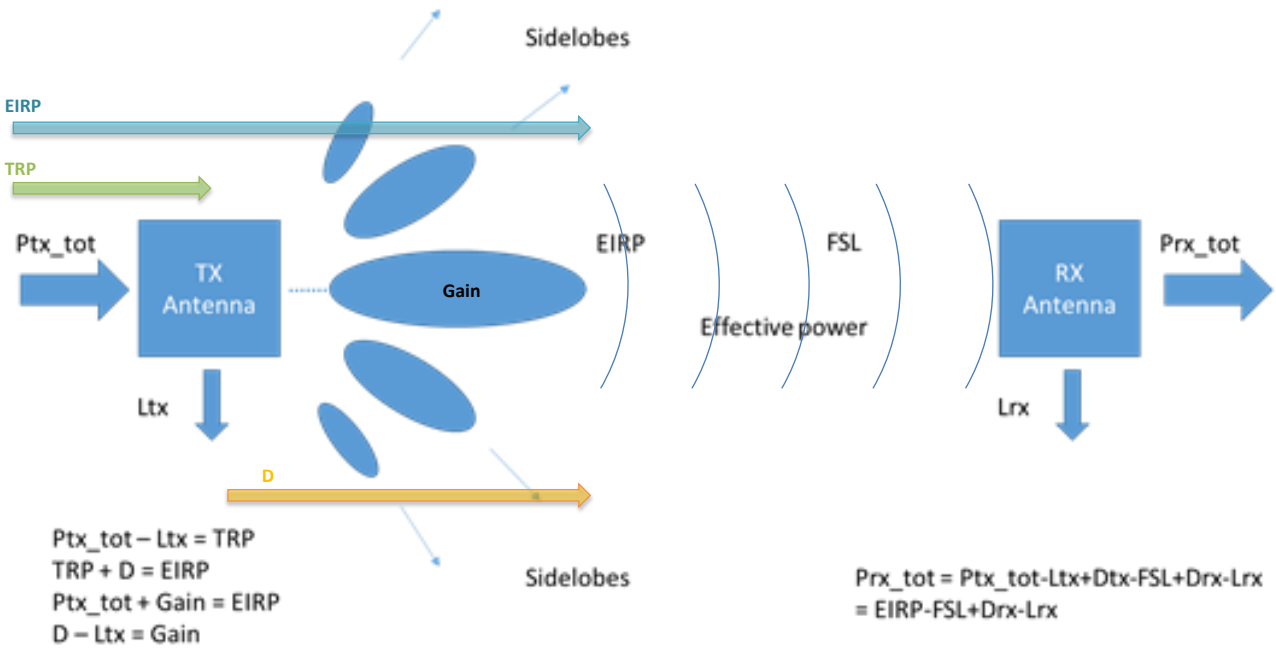
φ : azimuth angle in radians

$P(\theta, \varphi)$: power radiated by an antenna array system in the direction (θ, φ).

TRP is equal to the total conducted power input into the antenna array system less any losses in the antenna array system. Figure 7-2 illustrates the different relevant parameters e.i.r.p., TRP, and directivity D of a radio link.

FIGURE 7-2

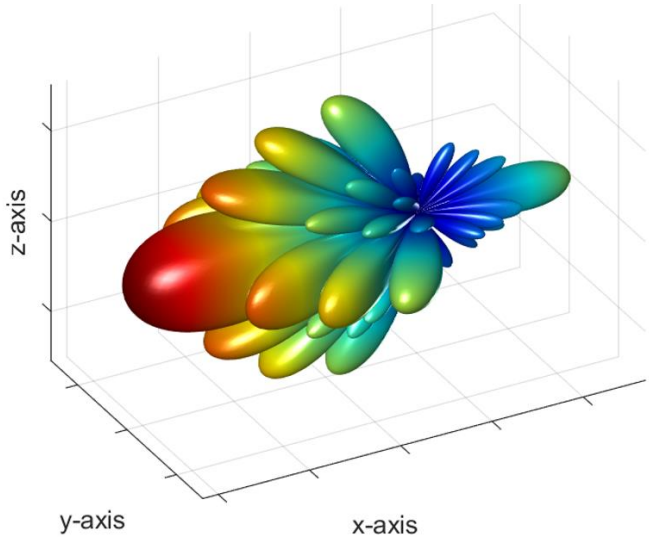
Illustration of directivity, e.i.r.p. and TRP



A graphical presentation of a 3D antenna pattern is shown in Fig. 7-3. The TRP is the volume of the whole structure.

FIGURE 7-3

3D polar plot of an 8x8 antenna array radiation pattern



7.3.4 Estimation of the TRP by field strength measurements

To achieve an absolutely accurate value for the TRP, the whole sphere around the transmit antenna would have to be measured, which is normally not possible in practice. The TRP can be determined by measuring the e.i.r.p. only if the directivity of gain of the transmitter antenna towards the measurement location is known. Otherwise, the TRP can only be estimated by a series of e.i.r.p. measurements in different directions covering the main beam.

The main situations where monitoring services have to determine the TRP of a transmitter is when measuring cellular base stations using active antenna systems, as most of the limits for these systems are defined in TRP. One of the practical challenges for monitoring services is that usually active antenna arrays do not have a test port between the amplifier and antenna that could be used for conducted measurements, so all measurements have to be done over the air.

3GPP TS 37.145-2 defines a method to obtain an estimate of the TRP from determined e.i.r.p. values as follows:

$$TRP_{Estimate} = \frac{\pi}{2NM} \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} EIRP(\theta_n, \varphi_m) \sin \theta_n \qquad (7\text{-}13)$$

where:

N : number of samples in the θ angle

M : number of samples in the φ angle.

Each (θ_n, φ_m) is a measurement sampling point. The sampling angular intervals for θ and φ are $\Delta\theta = \frac{\pi}{N}$ and $\Delta\varphi = \frac{2\pi}{M}$.

Under certain conditions it may be possible to derive a TRP estimate from a measurement at a single location. The measured power density of the signal can be expressed as follows:

$$P_D = \frac{P_{rx}}{A} \quad \text{or} \quad P_D = \frac{P_{rx} 4\pi}{G(\theta_2, \varphi_2)\lambda^2} \qquad (7\text{-}14)$$

where P_{rx} is the power measured at the signal analyser input RF port, A is the antenna aperture area and θ_2, φ_2 are the vertical angles from BS antenna to the test point.

The e.i.r.p. of the signal towards a measurement antenna located under a certain vertical and horizontal angle, $EIRP_{test}(\theta_2,\varphi_2)$, can be expressed as:

$$EIRP_{test}(\theta_2, \varphi_2) = 4\pi r^2 P_D = \frac{P_{rx}(4\pi r)^2}{G(\theta_2,\varphi_2)\lambda^2} \quad (7\text{-}15)$$

where r is the distance between transmit and measurement antenna, and $G(\theta_2,\varphi_2)$ is the measurement antenna gain towards the transmit antenna. The TRP of the signal equals:

$$TRP_{test} = \frac{EIRP_{test}(\theta_2,\varphi_2)}{D(\theta_1,\varphi_1)} \quad (7\text{-}16)$$

where $D(\theta_1,\varphi_1)$ is the directivity in the direction towards the measurement antenna. This information has to be provided by the BS manufacturer.

Details and measurement methods to estimate TRP can be taken from ECC Report 345 and Report ITU-R SM.2567-0.

7.3.5 Propagation influence

The time-varying changes in the basic transmission loss (see Recommendation ITU-R P.341 for the definition of basic transmission loss) influences the results. By averaging the measured data over a longer period of time the accuracy is increased. The influence of propagation effects increases with the distance between transmitter and receiving station, and if there is no LoS between them. Also, the behaviour of the transmitters in the neighbouring channels is important.

References

Report ITU-R SM.2567 – *Total Radiated Power (TRP) by measurements of e.i.r.p. in the field including aspects of accuracy*

ECC Report 345 – *In-band measurement methodologies for 5G AAS base stations in the field*

7.4 Propagation models

When radio waves propagate in a homogeneous ideal dielectric medium of infinite extent, they are subject to free space propagation. In such a situation, radio-wave propagation is influenced neither by the atmosphere nor by any terrain obstacles. The transmitted power decreases with the square of the distance and the free-space basic transmission loss given by (see Recommendation ITU-R P.525):

$$L\ (\text{dB}) = 20\log_{10} f(\text{MHz}) + 20\log_{10} d(\text{km}) + 32.45 \quad (7\text{-}17)$$

In more practical situations, radio-wave propagation between transmitter and receiver is usually influenced by many different effects, which can in turn, reduce or enhance the received signal. Such effects arise from:

– the neutral atmosphere or ionosphere;

– the terrain, including the Earth's surface, terrain irregularities, buildings and vegetation.

An accurate radio-wave propagation prediction method is a valuable tool for assessing the probability of receiving a particular transmission at a certain power or signal strength, at a given location, or percentage of locations and for a specified percentage of time. Comparison between the predicted and measured values will provide useful information for monitoring purposes, e.g. identification of excessively high values of received signal level. Such comparisons can be done automatically in real time by storing the predicted and measured values in databases.

7.4.1 Effects of the atmosphere

The Earth's atmosphere influences radio-wave propagation. It is necessary to distinguish between the effects due to the neutral atmosphere, e.g. the troposphere, and those due to the ionized part of the atmosphere – the ionosphere. The height of the troposphere extends from about 9 km at the Earth's poles to about 17 km at the equator. The height of the ionosphere extends from about 50 km to approximately 2 000 km. The properties of the troposphere are particularly important for propagation at frequencies above about 30 MHz and those of the ionosphere for frequencies on terrestrial parts below about 30 MHz. It should be noted however, that

significant trans-ionospheric effects (on Earth-space paths) can occur at frequencies extending up to several GHz.

7.4.1.1 Effects below about 30 MHz

In general, at frequencies between about 9 kHz and 30 MHz, two types of propagation are to be considered: ground-wave propagation along the Earth's surface and sky-wave, or ionospheric propagation. Ground-wave propagation refers to propagation within LoS as well as diffraction beyond the horizon. The propagation of a ground-wave signal depends mainly on the electrical characteristics of the ground and the radio frequency. The attenuation is lower over surfaces with a high conductivity. Sky-wave propagation is caused by refraction or reflection from the ionosphere. At ELF and VLF, electromagnetic waves may propagate in a wave guide mode in the lower ionosphere. Theoretical curves for ground-wave propagation are given in Recommendation ITU-R P.368. The recommended radio-wave propagation prediction method for HF sky-wave propagation is in Recommendation ITU-R P.533.

7.4.1.2 Effects above about 30 MHz

Variations in the refractive index of the neutral atmosphere greatly influence radio-wave propagation at frequencies above about 30 MHz. At frequencies greater than about 6 GHz, effects due to precipitation become significant and as the frequency increases, other effects such as those due to atmospheric gases, water vapour and clouds should also be considered. The refractive index of the troposphere decreases slightly with height. Variations in refractive index and its vertical gradient caused by changes in temperature, pressure and humidity can influence the propagation range of a signal. Of particular significance is the case where the vertical gradient becomes more negative than that of the standard atmosphere. Under such signal enhancement conditions (referred to as super-refraction or ducting), radio-wave propagation ranges can extend well beyond those normally expected, thereby providing the potential for interference when frequencies are shared. The behaviour of atmospheric refractivity is treated in Recommendations ITU-R P.453 and ITU-R P.834. Other ITU-R Recommendations dealing with radio-meteorological effects are ITU-R P.676 – Atmospheric gaseous absorption and related effects; ITU-R P.835 – Reference atmospheres; ITU-R P.836 – Water vapour: surface density and total columnar content and ITU-R P.837 – Characteristics of precipitation for propagation modelling.

7.4.2 Effects of obstacles and irregular terrain

Features along the terrain also affect the propagation of radio waves, particularly when the frequency increases above about 30 MHz. Propagation mechanisms include diffraction, scattering and reflection from obstacles. It is important, therefore, to examine the propagation path to determine the degree of obstruction due to terrain and land-use obstacles.

7.4.2.1 Line-of-sight path

Although line-of-sight (LoS) may exist between the two antennas, the terrain and land-use objects influence the radio-wave propagation if there is insufficient clearance between the ray-path and the terrain obstacle. A commonly used criterion is that the propagation path should clear all obstacles by at least 0.6 times the first Fresnel zone distance, otherwise some excess loss due to diffraction may occur. When making a path clearance assessment, it is necessary to take into account the refractive bending of the ray by the atmosphere and for this, the concept of an effective Earth radius is often used (see Recommendation ITU-R P.530).

7.4.2.2 Diffraction over obstacles and irregular terrain

Many radio-wave propagation paths encounter one or several separate obstacles between the antennas, and the resulting diffraction loss can be calculated using well-established methods such as those described in Recommendation ITU-R P.526. The influence of terrain irregularities, and thus excess loss due to diffraction increases with frequency. Other obstacles consisting of land-use, e.g. building, structures and vegetation could also contribute to excess loss due to diffraction and are considered in various ITU-R recommendations with such effects forming a sub-component of the radio-wave propagation prediction model, e.g. Recommendations ITU-R P.452 and ITU-R P.1812. Recommendation ITU-R P.2108 is dedicated to addressing the excess loss resulting from land-use (clutter) while Recommendation ITU-R P.833 provides models to address attenuation of radio wave propagating in vegetation.

7.4.3 Effects of reflections by the surface of the Earth

Electromagnetic waves are reflected from the surface of the Earth and, on a LoS path, a combination of the direct ray and the reflected ray may arrive at the receiving antenna. In the case of a perfectly conducting surface, the maximum received field strength of the combination of the two rays can reach (in theory) twice the value of the field strength of the direct ray when both signals are in phase but the waves will cancel for a phase difference of 180 degrees. The height of the antenna influences the phase of the arriving signals and thus the magnitude of the resulting signal. Techniques are available for reducing the reflected signal on a LoS path thereby avoiding interference effects between the two rays (see Recommendation ITU-R P.530).

Earth surface observation systems and space-based system receiving signals from the Earth are also affected by reflections from the sea surface. Such reflected signals may be comprised of coherent bistatic scattering coefficient and diffuse (non-coherent) bistatic scattering coefficient components that are modelled in Recommendation ITU-R P.2146.

7.4.4 Propagation on Earth-space paths

Methods for predicting the radio-wave propagation effects of wanted signals on slant paths, for the frequency range 1-55 GHz, are treated in Recommendation ITU-R P.618. Where appropriate, the Recommendation refers to other Recommendations in the ITU-R P-series, particularly those containing radio-meteorological information and data. Recommendation ITU-R P.619 provides radio-wave propagation prediction models for addressing interference between stations in space and on the surface of the Earth in the frequency range 0.1-100 GHz.

7.4.5 Available propagation models

There are many propagation prediction methods available for point-to-area and point-to-point communications, both for terrestrial and slant paths, depending on frequency range, services, wanted or unwanted signals, etc. Therefore, it is impossible to make a complete overview, but the reader's attention is drawn to the *Guide to ITU-R radio-wave propagation prediction methods*, which is a guide to the application of the propagation methods contained in the ITU-R P-series Recommendations. A few of these Recommendations are mentioned below.

Recommendation ITU-R P.368 contains ground-wave propagation curves for frequencies from 10 kHz up to 3 MHz. These are for antennas located on the Earth's surface and apply to an exponential atmosphere. No account is taken of irregular terrain. Ground-wave propagation is mainly governed by the electrical characteristics of the ground. The electrical characteristics may be expressed by three parameters: the permeability, the permittivity and the conductivity (see Recommendation ITU-R P.527). This conductivity is the most important electrical characteristic for frequencies below 3 MHz. Recommendation ITU-R P.832 contains the World Atlas of Ground Conductivities. The software integral to Recommendation ITU-R P.368 can be used to reproduce the field strength value curves and to calculate field strength values for a specific situation.

Recommendation ITU-R P.1546 contains the method for point-to area predictions for terrestrial services in the frequency range 30 to 3 000 MHz. As can be seen from the title, this Recommendation covers an extended frequency range. But also, the distance range on which prediction calculations can be made is extended from 1 to 1 000 km.

Recommendation ITU-R P.526 is a general physical method for calculating excess loss due to diffraction around/over one or more obstacles.

Various empirical models for propagation in urban areas have been developed (e.g. Hata- Okumura and Walfish-Ikegami) and converted to computerized versions. Such models are employed mainly in planning cellular radio systems. Recommendation ITU-R P.1411 provides prediction methods for short range outdoor propagation in the frequency range 300 MHz to 100 GHz and includes situations where antennas at both ends of the path are obstructed.

Various software implementations of ITU-R P-series Recommendations can be obtained from the ITU-R Study Group 3 web page on software, data and validation examples.

The ePropagation portal (https://www.itu.int/ITU-R/eTerrestrial/ePropagation), offers the possibility for TIES users to perform point to point and point to area propagation predictions using Recommendations ITU-R P.452, ITU-R P.1546 and ITU-R P.1812.

7.4.6 Propagation models and usage of various frequency bands

Table 7-7 describes the usage of various frequency bands from 3 kHz to 300 GHz, based principally on propagation characteristics. Consult the *Guide to ITU-R radio-wave propagation prediction methods* which provides a general guide to the application of the radio-wave propagation prediction methods of the Radiocommunication Study Group 3, indicating the specific limits of validity of frequency, distance and other aspects of each Recommendation and method.

TABLE 7-7

Propagation models and usage of various frequency bands

Band	Frequency	Mode	Range	Examples of usage	Rec. ITU-R
VLF	3-30 kHz	Waveguide	several 1 000 km	Worldwide, long range radionavigation and radiocommunications	P.684
LF	30-300 kHz	ground-wave, sky-wave	several 1 000 km	Long range radionavigation and radiocommunications	P.368; P.1147
MF	0.3-3 MHz	ground-wave, sky-wave	a few 1 000 km	Medium range point-to-point, broadcasting and maritime mobile	P.368, P.1147
HF	3-30 MHz	sky-wave	up to several 1 000 km	Long and short range point-to-point, broadcasting, mobile	P.533
VHF	30-300 MHz	space-wave, tropospheric scatter, diffraction	up to a few 100 km	Short and medium point-to-point, mobile, LAN, broadcasting (sound and TV), personal communications	P.617, P.1546, P.2001
UHF	0.3-3 GHz	space-wave, tropospheric scatter, diffraction, line-of-sight	less than 100 km	Short and medium point-to-point, mobile, LAN, broadcasting (sound and TV), personal communications, satellite communications	P.452, P.530, P.617, P.618, P.619, P.1238, P.1411, P.1546, P.1812, P.2001, P.2041, P.2108
SHF	3-30 GHz	Line-of-sight	less than 30 km	Short range point-to-point, broadcasting-satellite (sound and TV), LAN, mobile/ personal communications, satellite communications, radionavigation	P.452, P.530, P.618, P.619, P.1410, P.1411, P.1853, P.2001, P.2041, P.2108
EHF	30-300 GHz	Line-of-sight	less than 20 km	Short range point-to-point, microcellular, LAN and personal communications, satellite communications	P.618, P.619, P.1238, P.1410, P.1411, P.2001, P.2041

References

ITU-R Recommendations and Reports

NOTE – In every case, the latest edition of the Recommendation and Report is encouraged to be used.

Recommendation ITU-R P.310 – *Definitions of terms relating to propagation in non-ionized media*

Recommendation ITU-R P.368 – *Ground-wave propagation curves for frequencies between 10 kHz and 30 MHz*

Recommendation ITU-R P.452 – *Prediction procedure for the evaluation of interference between stations on the surface of the Earth at frequencies above about 100 MHz*

Recommendation ITU-R P.453 – *The radio refractive index: its formula and refractivity data*

Recommendation ITU-R P.525 – *Calculation of free-space attenuation*

Recommendation ITU-R P.526 – *Propagation by diffraction*

Recommendation ITU-R P.527 – *Electrical characteristics of the surface of the Earth*

Recommendation ITU-R P.530 – *Propagation data and prediction methods required for the design terrestrial line-of-sight systems*

Recommendation ITU-R P.533 – *Method for the prediction of the performance of HF circuit*

Recommendation ITU-R P.618 – *Propagation data and prediction methods required to design Earth-space telecommunication systems*

Recommendation ITU-R P.619 – *Propagation data required for the evaluation of interference between stations in space and those on the surface of the Earth*

Recommendation ITU-R P.676 – *Attenuation by atmospheric gases and related effects*

Recommendation ITU-R P.832 – *World Atlas of Ground Conductivities*

Recommendation ITU-R P.834 – *Effects of tropospheric refraction on radiowave propagation*

Recommendation ITU-R P.835 – *Reference atmospheres*

Recommendation ITU-R P.837 – *Characteristics of precipitation for propagation modelling*

Recommendation ITU-R P.1411 – *Propagation data and prediction methods for the planning of short-range outdoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz*

Recommendation ITU-R P.1546 – *Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 4 000 MHz*

Recommendation ITU-R P.1791 – *Propagation prediction methods for assessment of the impact of ultra-wideband devices*

Recommendation ITU-R P.1812 – *A path-specific propagation prediction method for point-to-area terrestrial services in the frequency range 30 MHz to 6 GHz*

Recommendation ITU-R P.2001 – *General purpose wide-range terrestrial propagation model in the frequency range 30 MHz to 50 GHz*

Recommendation ITU-R P.2041 – *Prediction of path attenuation on links between an airborne platform and Space and between an airborne platform and the surface of the Earth*

Recommendation ITU-R P.2108 – *Prediction of clutter loss*

Recommendation ITU-R P.2145 – *Digital maps related to the calculation of gaseous attenuation and related effects*

Report ITU-R P.2011 – *Propagation at frequencies above the basic MUF*

Report ITU-R P.2089 – *The analysis of radio noise data*

Report ITU-R P.2090 – *Measuring the input parameters for the radiative energy transfer model of vegetation attenuation*

Report ITU-R P.2097 – *Transionospheric radio propagation – The Global Ionospheric Scintillation Model (GISM)*

ITU-R Handbooks

Handbook [1991] Curves for Radiowave Propagation over the Surface of the Earth (https://www.itu.int/pub/R-HDB-13)

Handbook [1998] Ionosphere and its Effects on Radiowave Propagation (https://www.itu.int/pub/R-HDB-32)

Handbook [2013] Radiometeorology (https://www.itu.int/pub/R-HDB-26)

Handbook [1996] Radiowave Propagation Information for Predictions for Earth-to-Space Path Communications (https://www.itu.int/pub/R-HDB-27)

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Handbook [2008] Radiowave propagation information for designing terrestrial point-to-point links (https://www.itu.int/pub/R-HDB-54)

Handbook [2012] ITU-R propagation prediction methods for interference and sharing studies (https://www.itu.int/pub/R-HDB-58)

7.5 Intermodulation

7.5.1 Background

Unwanted emissions which consist of spurious and out-of-band emissions may interfere with licensed radio-communication systems. The most commonly encountered types of spurious emissions are harmonic emissions or intermodulation products, which are produced in a non-linear device such as the output amplifier of a transmitter. Such transmitted emissions are undesired spurious outputs, which can cause interference.

Intermodulation products (IMP) are produced in a non-linear device when two (or more) signals interact and generate an undesired signal. An undesired IMP can cause interference when it is:

– at or near the tuned frequency of a receiver; or

– at any other frequency to which a receiver is susceptible, such as the intermediate frequency (IF) of a superhetrodyne receiver.

IMP can be produced in transmitters or multi-channel output amplifiers (and radiated). They can also be produced in distribution amplifiers or in receiver input and IF stages. It is important for the monitoring operator, when resolving interference cases, to be able to determine whether a legitimate signal or an intermodulation product is being measured.

7.5.2 Intermodulation analysis equations

In many cases, intermodulation products are most difficult to detect and identify at a monitoring station, and this is why the following sections are mainly devoted to intermodulation analysis, detection and identification.

The following analysis only considers in-band intermodulation products (i.e. products whose frequencies are close to the input signal frequencies). Intermodulation interference is defined by any of the following equations:

Two Signal Case:

3rd order: $2T_{f1} - T_{f2} = R_f \pm BW$

5th order: $3T_{f1} - 2T_{f2} = R_f \pm BW$

7th order: $4T_{f1} - 3T_{f2} = R_f \pm BW$

Three Signal Case:

3rd order: $T_{f1} - T_{f2} + T_{f3} = R_f \pm BW$

5th order: $2T_{f1} - 2T_{f2} + T_{f3} = R_f \pm BW$

$3T_{f1} - T_{f2} - T_{f3} = R_f \pm BW$

7th order: $2T_{f1} - 3T_{f2} + 2T_{f3} = R_f \pm BW$

$3T_{f1} - 3T_{f2} + T_{f3} = R_f \pm BW$

$4T_{f1} - 2T_{f2} + T_{f3} = R_f \pm BW$

where:

T_f : transmitter frequency

R_f : receiver frequency

BW : receiver bandwidth.

A practical example of an IMP:

The transmitted frequencies are $f_1 = 232$ MHz (mobile channel), $f_2 = 229.75$ MHz (Sound Carrier of TV channel 12, for European Standard B) and the interfered frequency is 234.25 MHz (another mobile channel): thus IMP = $2T_{f1} - T_{f2} = 2 \times 232 - 229.75 = 234.25$.

Usually, intercept points and noise figures are given by manufacturers to characterize amplifiers and receivers. The following can be calculated from this data:

a) receiver noise level u_N for given values of measurement bandwidth B_{3dB} (Hz), noise figure NF (dB) and detector weighting factor W (dB):

$$u_N = -67 \text{ dB}(\mu\text{V}) + NF + 10 \log (B_{3dB}) + W \qquad \text{dB}(\mu\text{V})$$

The detector type weighting factor W is 0 dB for average, 1.1 dB for r.m.s., typically 7 dB for quasi-peak, and typically 11 dB for peak.

For example, for $NF = 10$ dB, $B_{3dB} = 9$ kHz, average detector:

$$u_N = -67 + 10 + 39.5 = -17.5 \qquad \text{dB}(\mu\text{V})$$

b) level of the intermodulation product u_{IMP} for given values of 3rd order intercept point IP_3 and individual level of two IMP generating signals u_{IMS}:

$$u_{IMP} = IP_3 - 3(IP_3 - u_{IMS}) \qquad \text{dB}(\mu\text{V})$$

For example, for $IP_3 = 20$ dBm = 127 dB(μV), $u_{IMS} = 80$ dB(μV), input resistance = 50 Ω:

$$u_{IMP} = 127 - 3\ (127 - 80) = -14 \qquad \text{dB}(\mu\text{V})$$

c) level of the intermodulation product u_{IMP} for given values of 2nd order intercept point IP_2 and individual level of two IMP generating signals u_{IMS}:

$$u_{IMP} = IP_2 - 2\ (IP_2 - u_{IMS})$$

For example, for $IP_2 = 50$ dBm = 157 dB(μV), $u_{IMS} = 80$ dB(μV):

$$u_{IMP} = 157 - 2\ (157 - 80) = 3 \qquad \text{dB}(\mu\text{V})$$

Intermodulation-free dynamic range:

1) calculate the noise level u_N

2) calculate the individual level of the two IMP generating signals using: $u_{IMS} = 1/3\ (u_N + 2\ IP_3)$, where all units are in dB(μV)

3) calculate: $D_{IMF} = u_{IMS} - u_N$ for the intermodulation free dynamic range.

For example, for NF = 10 dB: B_{3dB} = 9 kHz, IP_3 = 20 dBm, average detector:

$$u_{IMS} = 1/3\ (-17.5 + 2(127)) = 78.8\ \text{dB}(\mu\text{V})$$

$$D_{IMF} = 78.8 - (-17.5) = 96.3\ \text{dB}.$$

Detailed analysis of IMP created in transmitters appears in Recommendation ITU-R SM.1446 and Report ITU-R SM.2021. Recommendation ITU-R SM.1134 presents a method for calculation of IMP produced in receivers that helps determine levels of IMP up to 5th order. An example of calculations is also given.

7.5.3 Detection and identification of intermodulation products

The practical situation confronted by the operator of a monitoring receiver is determining whether an observed signal is a legitimate signal delivered to the receiver by the antenna or an IMP generated in the receiver by two or more strong signals. A first indication that IMPs are present in the receiver's output often is the observation of what appears to be the same signal modulation on more than one frequency.

A simple test for IMP is to insert a known amount of attenuation in front of the input of the receiver. If the observed signal amplitude decreases by the amount of the known added attenuator, then the observed signal is legitimate. If the amplitude decreases by an integer multiple of the attenuator value, then the observed signal is an IMP of the order of the integer multiple, that is produced in the receiver. If the IMP is generated both internally and externally, the observed signal will drop by more than the added attenuation but would not be an integer multiple of the attenuator value.

For example, if 10 dB is inserted and the amplitude of the observed signal drops by 30 dB, then the observed signal was a 3rd order IMP. If the observed signal is fading, then the size of the attenuator should be sufficiently large so that decreases due to fading are not misinterpreted as changes due to IMPs. Care should be taken to avoid using an attenuator that is so large that, after attenuation, the signal falls below the level where it is at least 5 dB above the receiver's noise floor.

Alternatively, the built-in input attenuation of a spectrum analyser or measuring receiver can be used. Most such instruments keep their reference level constant as the input attenuation is changed; which gives a different criterion than when using uncoupled attenuation. If the observed signal amplitude stays constant, then the observed signal is legitimate. If the amplitude changes, the IMP is generated internally or is the sum of externally and internally generated products.

If a spectrum analyser is available, then various resolution bandwidths can be used to facilitate the detection and identification of IMPs. This approach is especially effective when there are many IMPs present simultaneously such that the apparent receiver noise floor is elevated across a wide frequency band.

Finally, IMPs can result from in-band signals (e.g. HF signals causing IMPs in the HF band) or from out-of-band signals (e.g. VHF signals causing IMPs in the HF band). Low-pass, high-pass and band-pass filters are useful with spectrum analysers for identifying IMPs and whether they are in-band products or out-of-band products. Spectrum analysers with digital storage, that have multiple traces and the ability to store and view a trace; make it easy to compare spectrums with and without filters to look for the presence or absence of the intermodulation products.

Spectrum analysers with 3-axis displays (amplitude versus frequency and time using multiple sweeps) are especially well adapted to the detection and identification of IMPs when observing the spectrum with and without the filters.

When trying to solve interference problems, it is useful to determine if the interference results from IMPs produced in the transmitter or in the receiver. A large signal survey is useful to reveal potential causes of IMPs products. The intermodulation analysis equations can be used to look for a match between computed IMPs and the interfering signal.

Bibliography

ITU-R Recommendations and Reports

Recommendation ITU-R SM.329 – *Unwanted emissions in the spurious domain*

Recommendation ITU-R SM.1134 – *Intermodulation interference calculations in the land-mobile service*

Recommendation ITU-R SM.1446 – *Definition and measurement of intermodulation products in transmitter using frequency, phase, or complex modulation techniques*

Report ITU-R SM.2021 – *Production and mitigation of intermodulation products in the transmitter*

NOTE – In every case, the latest edition of the Recommendation and Report is encouraged to be used.

7.6 Modulation and spectrum access methods

7.6.1 Introduction

RF modulation is the variation of a sinusoidal electromagnetic carrier (voltage, current or field) by a signal. The purpose of modulation is to transpose the baseband signals, which in general have neither a suitable shape nor a directly transmittable frequency, to a higher frequency, which can be emitted via an antenna.

The modulating signal may change the amplitude or the frequency/phase of the carrier or both. It may be an analogue or a digital signal, e.g. a bit stream.

The designations of the types of modulations are listed in RR Appendix **1**.

Spectrum access methods define how and when a modulated signal has access to the spectrum resources. If signals from multiple sources (e.g. different users or transmitters) want to have access to the spectrum inside the same geographic area, access methods have to be applied to allow sharing of the resource without interference.

7.6.2 Analogue modulation

7.6.2.1 Amplitude modulation

If a carrier wave with the amplitude E_C (Fig. 7-4 a)) is amplitude-modulated by a sinusoidal oscillation (a tone) a wave is obtained as shown in Fig. 7-4 b). In these figures, the abscissa represents time and the ordinates the voltage (or current) of the wave ("time domain presentation").

The amplitude will thus change with the modulating sine wave signal, to which the envelope of the carrier wave will correspond.

If the amplitude of the modulating signal is increased, the variation in amplitude of the modulated wave will likewise increase up to the point where an instantaneous suppression of the envelope takes place, as shown in Fig. 7-4c).

If the maximum amplitude of the modulated wave is E_{max}, and the minimum amplitude of the envelope E_{min} (see Fig. 7-4 b)), the modulation depth m is given by:

$$m = \frac{E_{max}-E_{min}}{E_{max}+E_{min}} \quad \text{or expressed as percentage:} \quad m(\%) = \frac{E_{max}-E_{min}}{E_{max}+E_{min}} \tag{7-18}$$

If the amplitude of the modulating signal is increased further, the maximum amplitude of the wave will also increase, but there will be a break in the wave for a short period of time, as shown in Fig. 7-4 d). This is called overmodulation.

In order to detect overmodulation using the equations (7-18), the system has to be able to determine a value of $E_{min} < 0$.

Alternatively, other definitions can be used for m which are related to the average voltage E_c.

These definitions give the same values as equation (7-18) for sinusoidal modulation waveforms, but with the advantage that symmetry and overmodulation are defined.
Using E_{max} and E_c is obtained:

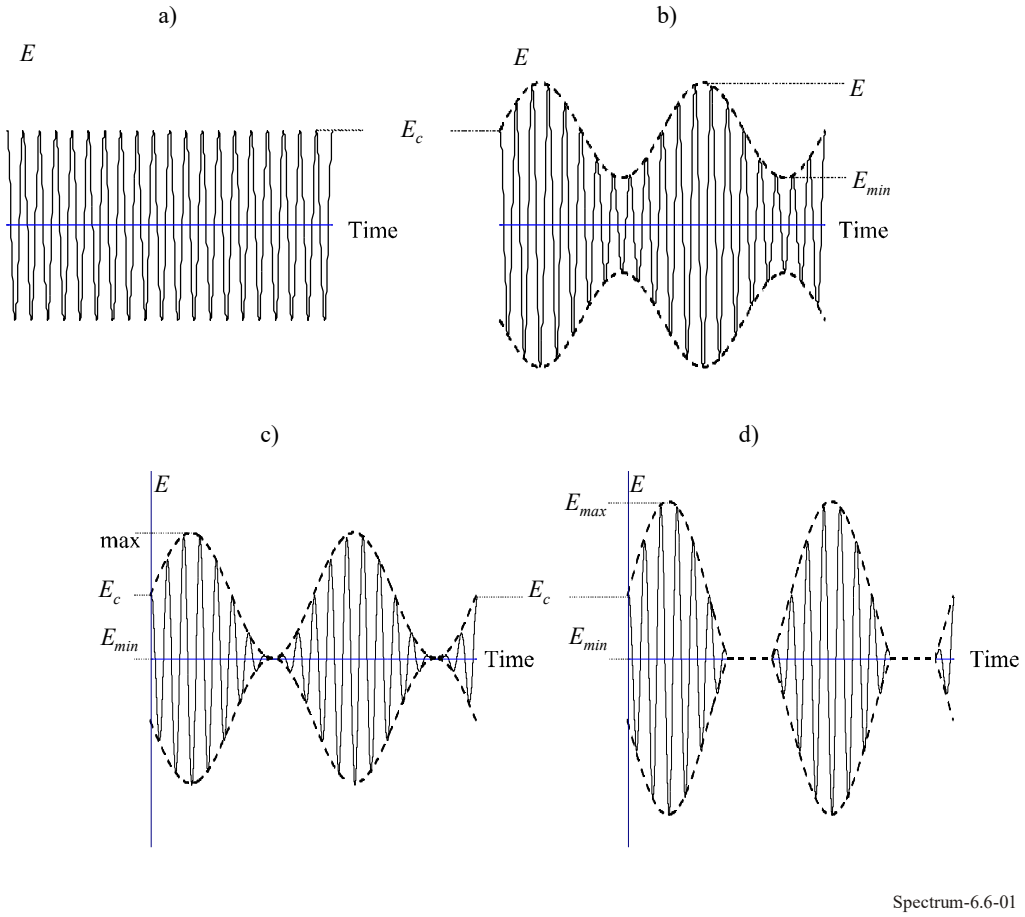
$$m_+(\%) = \frac{E_{max} - E_c}{E_c} \times 100 \tag{7-19}$$

Using E_{min} and E_c is obtained:

$$m_-(\%) = \frac{E_c - E_{min}}{E_c} \times 100 \tag{7-20}$$

FIGURE 7-4

Time domain presentation of the amplitude-modulated signal



Taking into consideration E_{max}, E_{min} and E_c :

$$m_{+/-}(\%) = \frac{E_{max} - E_{min}}{2E_c} \times 100 \tag{7-21}$$

With $m_+ = m_- = m_{+/-}$, the modulation can be considered symmetrical, i.e. the value of the carrier amplitude ($= E_c$) is not changed by modulation and the modulation percentage is < 100% in any case which means no overmodulation takes place.

The modulation is called non-symmetrical if:

$$m_+ \neq m_- \neq m_{+/-}$$

When an overmodulated signal is received, a sine wave signal with clipped peaks is given at the audio-frequency output of the receiver instead of the sine wave signal used to overmodulate the transmitter.

This leads to appreciable distortion. Overmodulation and the resulting transmission impairment should therefore be avoided; moreover, overmodulation increases the bandwidth occupied by an emission.

Figure 7-5 shows the amplitude-modulated signals in the frequency domain ("spectrum presentation"). The abscissa represents the frequency and the ordinates the voltage or current of the wave.

As can be seen, the carrier modulated by one sinewave signal is accompanied by two sidebands whose frequencies are $f_c + f_m$ and $f_c - f_m$, each of them having the amplitude:

$$E_m = \frac{m}{2} \cdot E_c \tag{7-22}$$

The *occupied bandwidth* is:

$$(f_c + f_m) - (f_c - f_m) = 2f_m \tag{7-23}$$

e.g. twice the frequency of the modulating signal.

Figure 7-5 d) shows the spectrum of an overmodulated wave. Assuming that the over modulation causes distortion products up to the third harmonic of the modulating signal, the occupied bandwidth is three times the occupied bandwidth of the distortion-free modulated signal. Therefore, over modulation has to be avoided.

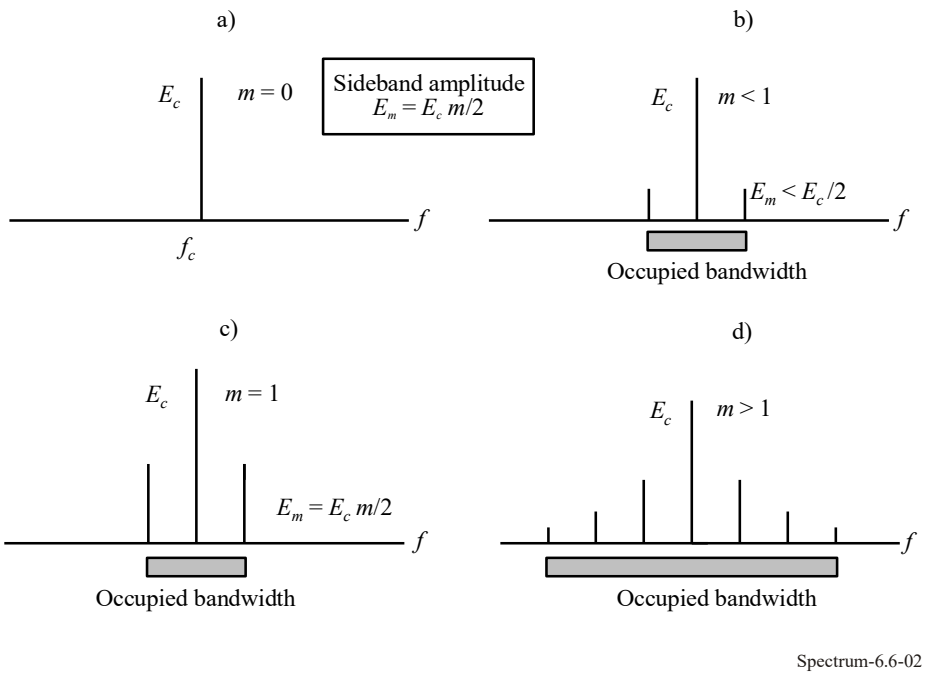
As can be seen from Fig. 7-4 a) and Fig. 7-4 c), the amplitude of the carrier and the occupied bandwidth remain unchanged if no over modulation occurs. Additional power is contained in the side-bands. The total power of a modulated wave is equal to the sum of carrier power and power of the sidebands. It is given by:

$$P_m = P_C \left(1 + \frac{m^2}{2}\right) \tag{7-24}$$

Overmodulation reduces the carrier amplitude.

FIGURE 7-5

Frequency domain presentation of the amplitude-modulated signal



7.6.2.2 Frequency modulation

A frequency-modulated signal is one whose instantaneous frequency is deviated in accordance with the modulating signal.

The waveform, for a sinusoidal modulating signal, is described by the following general equation:

$$s(t) = a * \cos[2\pi . f_c . t + m . \sin(2\pi . f_m . t)] \tag{7-25}$$

where:

a : amplitude of the frequency modulated signal

f_c : frequency of the carrier

f_m : frequency of the modulating signal and m is the index of modulation.

The index of modulation is proportional to the frequency deviation and is defined as:

$$m = \frac{\Delta f}{f_m} \tag{7-26}$$

Δf is the frequency deviation.

The frequency domain is more interesting than the time domain since it allows calculating the total energy of a frequency modulation (FM) signal.

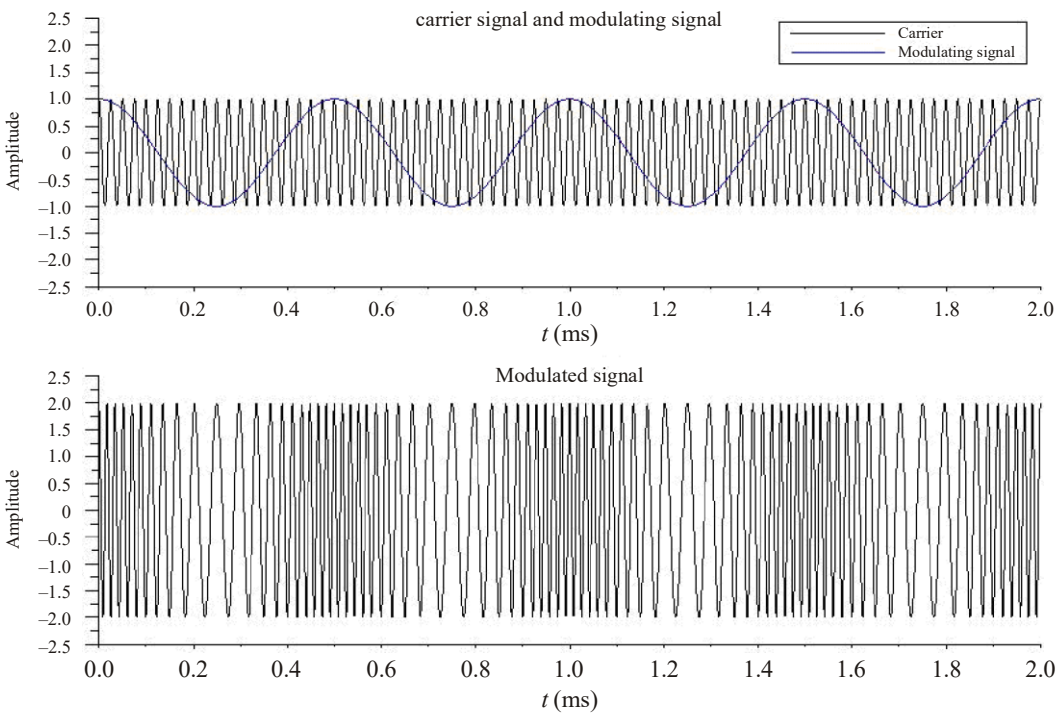
By applying fast Fourier transform (FFT) reckoning on the time domain equation, the spectrum is described by the following general relation:

$$S(\omega) = a.\sum_{k=-\infty}^{+\infty} m\left(\omega_p - k.\omega_m\right).J_k(m) \tag{7-27}$$

$J_k(m)$ terms are Bessel functions of the first kind which are represented below.

FIGURE 7-6

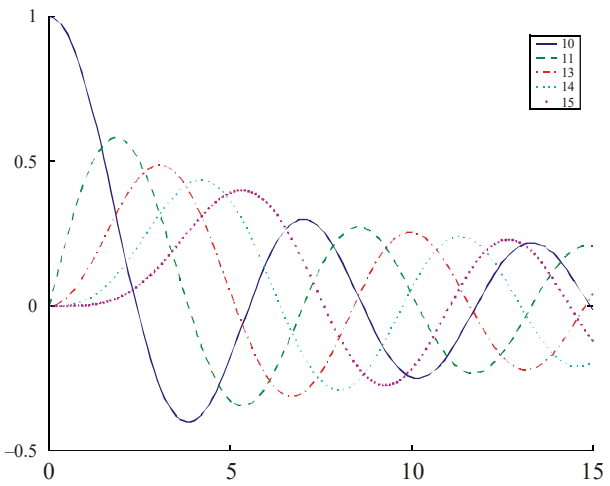
Time domain presentation of the frequency-modulated signal



Spectrum-6.6-03

FIGURE 7-7

Bessel function of the first kind



Spectrum-6.6-04

In theory, the FM signal is built by an infinite number of sideband pairs; practically speaking, 99% of the energy is included in a finite bandwidth which can approximately be defined as follows:

– for narrow band modulation (m ≤1), the bandwidth is equal to 2 x f_m;

– if the modulating signal is a continuous or broad spectrum of frequencies, the Carson's bandwidth rule is expressed as $2(\Delta f + f_m)$ or $2 \cdot f_m \cdot (m + 1)$.

Example:

f_c = 100 MHz, f_m = 2 kHz, Δf =10 kHz, m = 5

Reckoning of the bandwidth: B = 2*2k*(5 + 1) = 24 kHz.

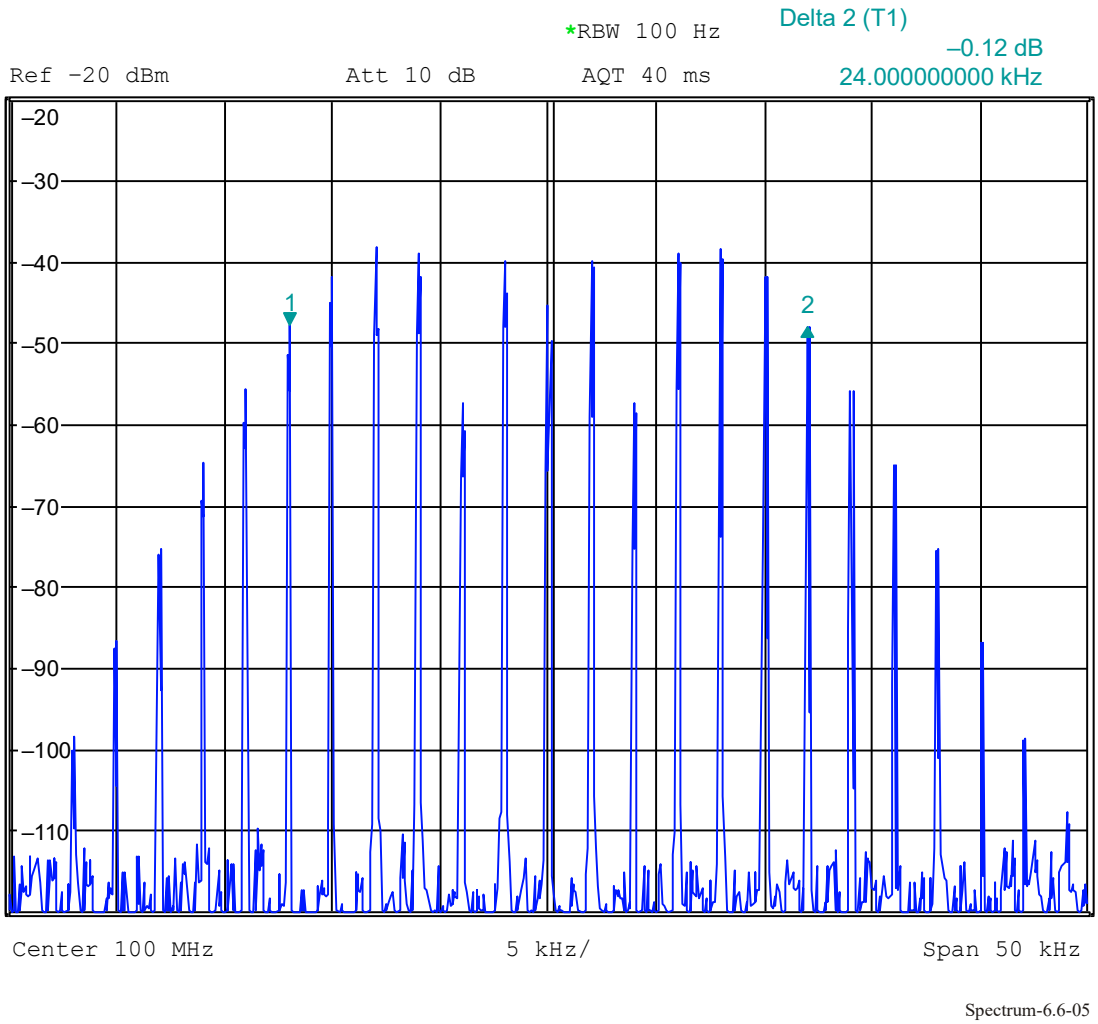
Computing of amplitude of each sideband pairs (Bessel function for m = 5):

Frequency	**Amplitude**	
f_c	$J_0(5)$	–0.18
$f_c \pm f_m$	$J_1(5)$	–0.33
$f_c \pm 2f_m$	$J_2(5)$	0.05
$f_c \pm 3f_m$	$J_3(5)$	0.36
$f_c \pm 4f_m$	$J_4(5)$	0.39
$f_c \pm 5f_m$	$J_5(5)$	0.26
$f_c \pm 6f_m$	$J_6(5)$	0.13
$f_c \pm 7f_m$	$J_7(5)$	0.05
$f_c \pm 8f_m$	$J_8(5)$	0.02
$f_c \pm 9f_m$	$J_9(5)$	0.005

Figure 7-8 shows the resulting FM spectrum for the example.

FIGURE 7-8

Example FM spectrum



7.6.2.3 Phase modulation

Phase modulation (PM) and Frequency modulation are principally the same: Changing the frequency also changes the momentary phase of the resulting RF signal relative to the start phase of the unmodulated signal, and vice versa.

Therefore, the same formulas as for FM also apply to PM, and the resulting spectra are equal. The only difference is the way the receiver demodulates the signal to retrieve the modulating information.

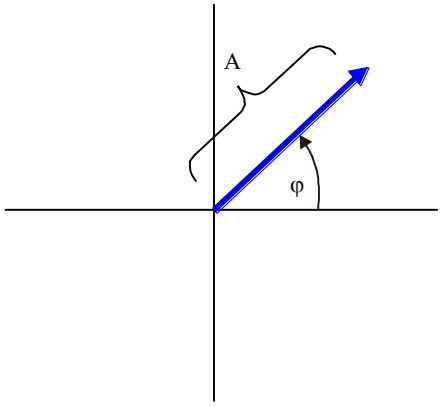
The frequency domain, however, is not suitable to symbolize phase modulation because only frequency and amplitude can be seen. A more common way to symbolize phase modulation is by using a polar diagram in which the RF signal is represented by a vector that starts at the centre. The length of the vector is the RF amplitude; the angle relative to the horizontal line is the momentary phase. Figure 7-9 shows an example.

An unmodulated carrier would be represented by a constant, steady vector. If the signal is frequency modulated, the vector would rotate left or right depending on the momentary frequency being lower or higher as the unmodulated carrier.

At the same time, the angle φ would also change constantly. So, modulating the frequency is in fact equal to modulating the phase.

FIGURE 7-9

Momentary polar diagram of a phase modulated signal



Spectrum-6.6-06

7.6.2.4 Special analogue modulations

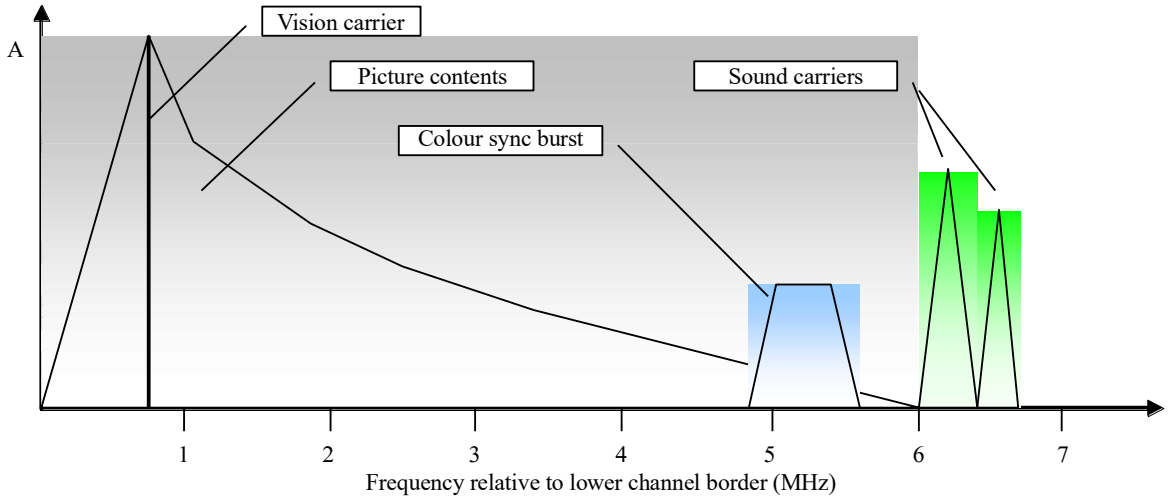
7.6.2.4.1 TV broadcast modulation

Analogue TV broadcast transmissions in the VHF/UHF bands use vestigial sideband modulation (VSB) (negative or positive) for the video signal and one or more separate sound carriers which are frequency- or amplitude-modulated.

The resulting spectrum is complex and the single components as well as their amplitude and frequency spacing relative to the carrier depends on the particular standard. Figure 7-10 shows a simplified example of an analogue colour vision signal together with stereo sound.

FIGURE 7-10

Simplified PAL TV spectrum with stereo sound



Spectrum-6.6-07

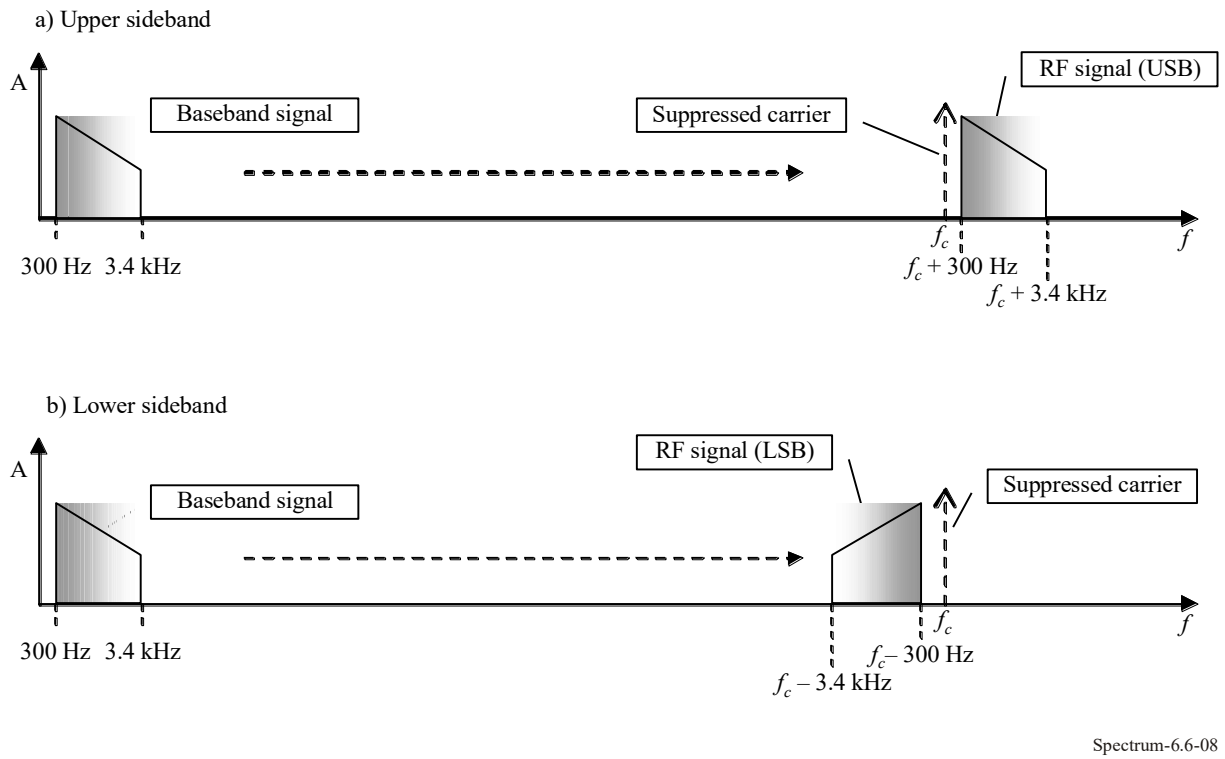
7.6.2.4.2 Single sideband modulation with suppressed carrier

Single sideband modulation with suppressed carrier (SSB or J3E) is widely used for narrow band voice transmissions. For this type of modulation, the telephony baseband is only shifted (or shifted and inverted) to

the assigned frequency, amplified and emitted via an antenna. In consequence, if there is no voice signal, then only the carrier remains but since it is suppressed, nothing is transmitted. Figure 7-11 illustrates the SSB principle.

FIGURE 7-11

SSB modulation principle



Generally, the upper sideband is used (USB, Fig. 7-11 a), only amateur stations use the lower sideband (LSB, Fig. 7-11 b).

The advantage of SSB compared to standard amplitude modulation (AM) is that it uses only half of the spectral bandwidth and does not waste transmitter power by emitting the carrier.

7.6.2.4.3 Independent sideband modulation

Independent sideband modulation (ISB) with suppressed carrier (B8E) work to the same principles as SSB, only that two independent audio basebands are transmitted: baseband 1 is shifted into the upper sideband; baseband 2 is inverted and shifted to the lower sideband range of the RF.

7.6.2.4.4 Dynamic amplitude modulation

The conventional two-sideband AM transmitter is – from the point of view of power consumption – a very uneconomical device. Even at a modulation depth m = 100% only 17% of the radiated power is used for the information (one sideband), and 66% is carrier power without any information content (see equation (7-24)).

For lower values of m the relations are even worse. As a solution to this problem several attempts were made to reduce the carrier power dynamically at times when the modulation depth m is low (which is the fact in practice for most of the time).

One solution is called dynamic amplitude modulation (DAM), which reduces the carrier power when m is significantly lower than 100%. Evidently, this procedure saves energy.

7.6.3 Digital modulation

7.6.3.1 Principles of digital modulation

The information in digital communications is transmitted in quantized form, i.e. the amplitude and/or the phase of the signal can only have discrete values. The information to be transmitted is a data stream consisting of "ones" and "zeros". The transmitter looks at the input bits with the speed of a so-called "clock rate". The receiver looks at the state of the RF signal with the same clock rate and decodes the source bit(s) accordingly.

Like analogue signals, digital baseband signals have neither a suitable shape nor an appropriate frequency to be emitted via an antenna. To enable transmission in a radio channel they have to be transposed to a higher frequency by modulating a sine wave RF carrier.

The data signal containing the information influences the amplitude, frequency and/or phase of the RF carrier at the clock rate of the data signal. The clock rate is also called the symbol rate. Amplitude and angular modulations are used simultaneously in some cases.

In digital techniques the word "modulation" is frequently replaced by the word "keying". The abbreviations ASK, FSK and PSK are used for amplitude shift keying, frequency shift keying and phase shift keying.

The advantage of digital signals is that they can be restored without any degradation by noise under certain circumstances.

7.6.3.2 Amplitude shift keying

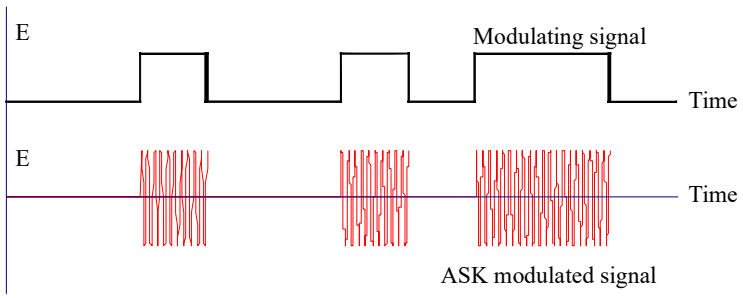
The simplest way of modulating the carrier wave with digital baseband signals is by amplitude shift keying (ASK). This is achieved, for example, by a signal, which switches the carrier on and off. If a 1 is to be transmitted, the carrier is switched on, for a "0" the carrier is off.

The classical example of this is the Morse code. If a carrier is merely switched on and off at the pulse rate of the data signal this is referred to as on-off keying (OOK). The modulating and modulated signals of this type of modulation are presented in Fig. 7-12.

In some cases, e.g. for standard-time signals, keying is less than 100%. This has the advantage that even when the data stream consists of multiple zeros, still some energy is transmitted so that the receiver does not lose the signal and keeps synchronized.

FIGURE 7-12

Amplitude shift keying



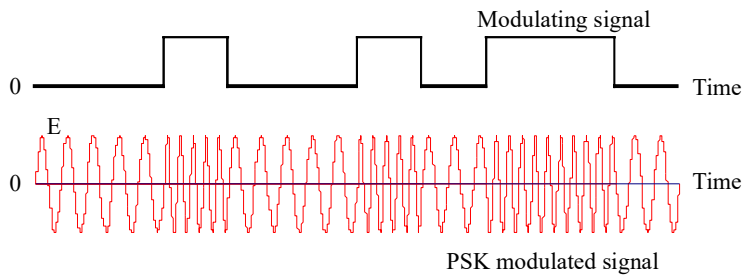
Spectrum-6.6-09

7.6.3.3 Frequency-shift keying

With FSK, the frequency of the carrier is altered according to the modulating signal: if a "1" is to be transmitted, the carrier frequency f_c is raised to f_1, during the transmission of a 0 it is lowered to f_2. The modulating and modulated signal of this type of modulation is presented in Fig. 7-13.

FIGURE 7-13

Frequency shift keying



Spectrum-6.6-10

The amplitude of the carrier wave remains constant whereas the frequency can assume two values:

$$f_1 = f_C + \Delta f \quad \text{and} \quad f_2 = f_C - \Delta f \tag{7-28}$$

For successful decoding, the spacing Δf depends on the clock rate: the higher the clock rate, the higher the spacing has to be.

7.6.3.4 Phase-shift keying

A third method for modulating a carrier wave with digital signals is phase shift keying (PSK). The modulating data signal and the modulated RF signal of this type of modulation are presented in Fig. 7-14.

As can be seen, the level of the modulated signal remains constant, but the phase is switched (in this example) by 180° if the modulating signal changes from "0" to "1" (2-PSK).

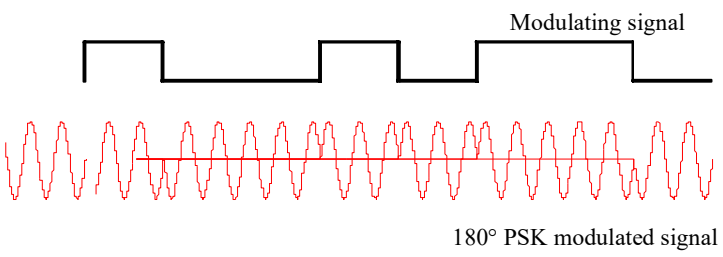
As with analogue phase modulation, the best way to symbolize PSK is a polar diagram like in Fig. 7-9.

However, it is most common to draw the RF vector only at those points in time where the receiver attempts to decode the signal. All possible states at that time are drawn in the same diagram.

To improve the reading, only the end points of the vectors are drawn as dots.

FIGURE 7-14

Phase shift keying

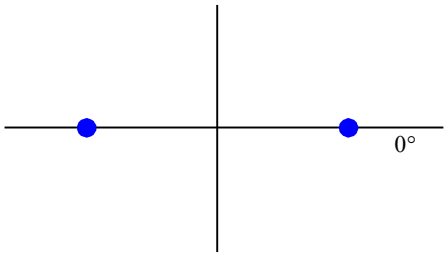


Spectrum-6.6-11

The resulting figure is called "constellation diagram". Figure 7-15 shows the constellation diagram of a 2-PSK.

FIGURE 7-15

Constellation diagram of a 2-PSK



Spectrum-6.6-12

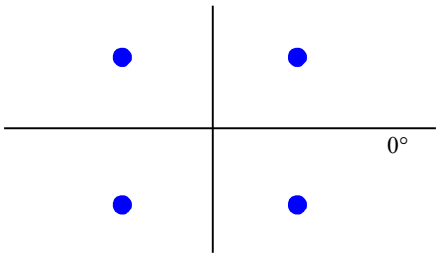
In all the examples of ASK, FSK and PSK used so far, the RF carrier can only have two allowed states at the time of decoding (ASK: carrier "on" or "off", FSK: frequency f_1 or f_2, PSK: phase "0°" or "180°"). These systems can therefore transmit one bit of source data per step. In these cases, the clock rate and the bit rate are equal.

If more than two distinct states of the RF carrier are defined, it is possible to transmit the information contained in two or even more bits in one step. An example is the so-called 4-PSK or Quadrature Phase Shift Keying (QPSK). The phase of the RF carrier at the decoding time can be 45°, 135°, 225° or 315°. The constellation diagram is shown in Fig. 7-16.

Each of the four constellation points represents two source bits. The bits that are transmitted in one step are called symbol. The connection between symbol and RF state (constellation point) is established through a coding scheme.

FIGURE 7-16

Constellation diagram of a QPSK



Spectrum-6.6-13

TABLE 7-8

Example of a coding scheme for QPSK

Symbol (source bits)	RF carrier phase
00	45°
01	135°
10	225°
11	315°

The number of symbols that are transmitted in 1 s is called the symbol rate. The RF carrier keeps changing its state with the speed of the symbol rate, but in the example of QPSK the bit rate is twice the symbol rate. This

principle allows increasing the bit rates without increasing the bandwidth because that only depends on the symbol rate. However, because the constellation points in QPSK are closer together as they are in 2-PSK, a higher signal-to-noise ratio is required for QPSK, making this modulation not as robust as 2-PSK.

Modern digital systems may also use higher order PSK modulation to combine 3 or more bits to a symbol.

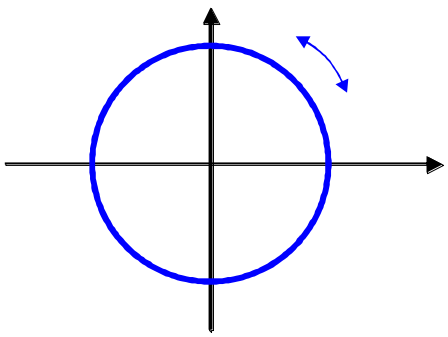
7.6.3.5 Minimum shift keying

Although all constellation points of a PSK signal have the same amplitude, this parameter is not constant for the whole time when the signal bandwidth is limited by filtering: On its way from one constellation point to the next, the length of the momentary RF vector changes and hence the RF amplitude. For example, in a 2-PSK like in Fig. 7-5, the direct way between the constellation point 0° to the opposite one at 180° is by going through the centre of the diagram. At that moment, the RF amplitude would even be zero.

An alternative way of modulating the RF phase (or frequency) is by going on a circle and keeping the amplitude constant. The information to be transmitted is then coded into the direction with which the RF vector rotates. The receiver only has to detect the rotation direction in order to decode the signal (e. g. left = 0, right = 1). As mentioned in § 7.6.2.3, rotating the RF vector is equal to raising or lowering the RF frequency. In order to detect the vector rotation correctly, the minimum possible change in the vector's angle between two steps (bits) is 90°. This modulation is called minimum shift keying (MSK). Figure 7-17 shows the "constellation" diagram of an MSK which is a circle, because the actual angles of the vector at each time of decoding are not defined.

FIGURE 7-17

MSK constellation diagram



Spectrum-6.6-14

Major advantages of MSK against PSK are that cheaper equipment can be used (e. g. linear amplifiers at the transmitter and simpler receivers), and that the RF signal is always present allowing continuous receiver synchronization and very low *S*/*N* ratios.

7.6.3.6 Quadrature amplitude modulation

When more than 3 bits have to be combined to a symbol, PSK is not ideal because the constellation points would come too close together, requiring more and more *S*/*N*.

Instead, both amplitude and phase of the constellation points is altered in a way that the constellation diagram is a square, evenly filled with constellation points. An example of 16-QAM is shown in Fig. 7-18.

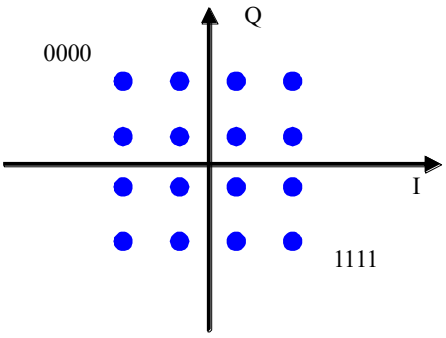
In a 16-QAM, 4 bits are combined to a symbol. If enough *S*/*N* can be assumed (for example in cable transmissions), 256-QAM with 8 bits per symbol are common and up to 1 024-QAM with 10 bits/symbol are sometimes used.

Modern transmitters employing digital signal processors (DSP)s do not actually alter the amplitude and phase of the RF carrier directly. Instead, the transmitted RF signal is composed of two component audio frequency (AF) signals amplitude modulating two RF carriers of the same frequency that have a constant phase offset of 90°. The components are called inphase (I) and quadrature phase (Q). In Fig. 7-18 the axes are labelled I and

Q accordingly. Each constellation point can be reached by changing (modulating) the amplitude of each component to a certain value.

FIGURE 7-18

Constellation diagram of a 16-QAM



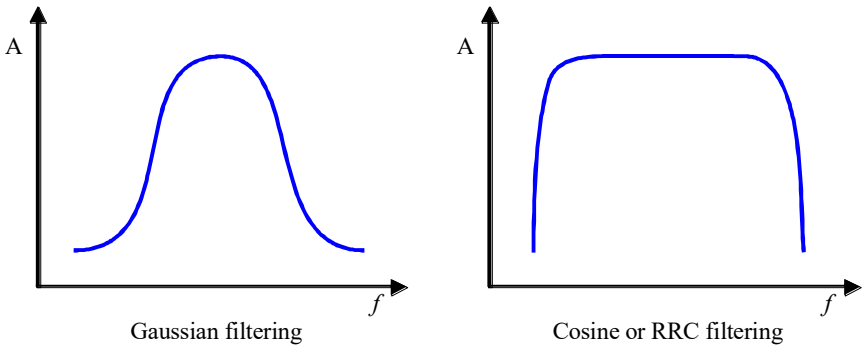
Spectrum-6.6-15

7.6.3.7 Baseband filtering for single carrier modulations

The digital modulating signal consisting only of "ones" and "zeros" has a rectangular time domain representation. If the RF signal would follow the digital data signal exactly, the resulting vector would have to change states (amplitude, frequency or phase) immediately each time the data signal has a slope. This would result in very broadband, radar-like RF spectra. Because the receiver only expects the RF vector to be on one of the constellation points at the time of decoding, it is possible to change states slowly in the time between two steps. This can be done by applying a low pass filter before the modulation process (i. e. in the baseband). The effect is that sharp edges in the time signal are avoided and the resulting RF bandwidth is reduced considerably. Due to certain constraints (no interference between one symbol and the next), only Gaussian and raised cosine filters can be used. Some systems split the cosine filter in a way that half of the filter is applied in the transmitter while the other half is applied in the receiver. These "half cosine" filters are called "Root Raised Cosine" or RRC filters. Figure 7-19 shows the spectrum shape of digital single carrier signals after the baseband filtering.

FIGURE 7-19

Spectra of filtered digital single carrier signals



Spectrum-6.6-16

7.6.3.8 Orthogonal frequency-division multiplex

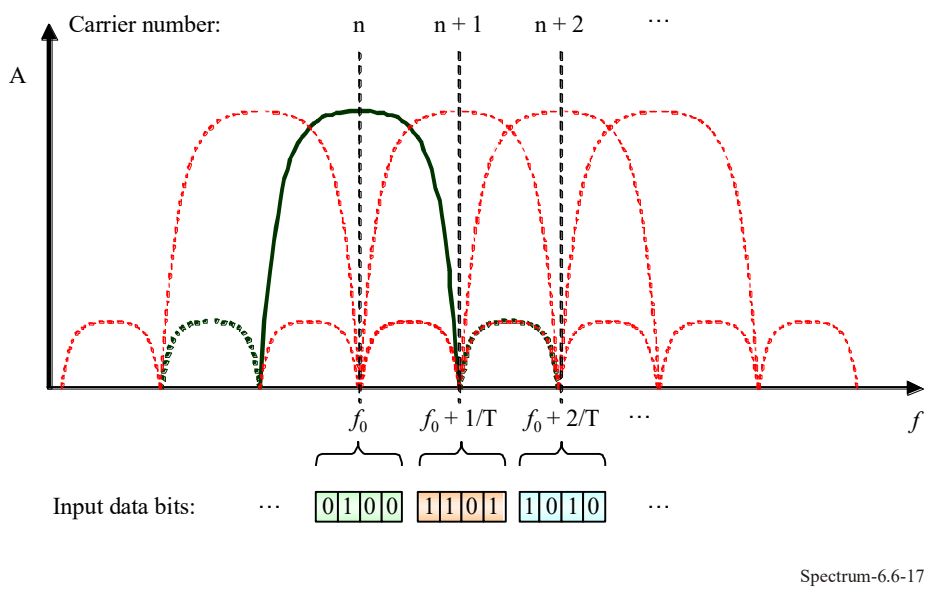
Orthogonal frequency-division multiplex (OFDM) is a method of combining a large number of digitally modulated carriers to form an ensemble [Carlson, 1986], [Lymer, 1994]. Depending on its modulation, each

carrier is modulated with the information contained in a number of bits (usually 4 or 6). The input data stream is therefore split in as many groups as there are OFDM carriers (up to a few thousand). Because all carriers are transmitted at the same time (in one step), the symbol size of an OFDM system is extremely high (several kbits), allowing very slow symbol rates while still maintaining a high useful data rate.

When the reference phase of neighbouring carriers has an offset of 90°, the carrier spacing can be as low as the symbol rate. Then spectra of the modulated carriers overlap without influencing the decoding of the neighbouring carriers. Figure 7-20 illustrates the forming of OFDM ensembles. The example uses 16-QAM modulation of the carriers, so that each carrier is modulated with a group of four bits.

FIGURE 7-20

OFDM carriers with 16-QAM modulation



The complete OFDM signals are generated using an inverse FFT and demodulated using a FFT.

Due to the overlapping spectra of the modulated carriers, the resulting complete OFDM spectrum has a rectangular shape like in Fig. 7-21 with a noise-like top line. The single carriers are not distinguishable.

As an example, one of the digital video broadcasting – terrestrial (DVB-T) systems used in Europe has 6 817 carriers, modulated with 64-QAM, each carrying 6 bits of information per step. The total symbol size is then:

$$6 * 6\,817 = 40\,902 \text{ bits}$$

The carrier spacing is 1.11 kHz, fixing the symbol rate to 0.9 ms. The gross data rate of this system is therefore:

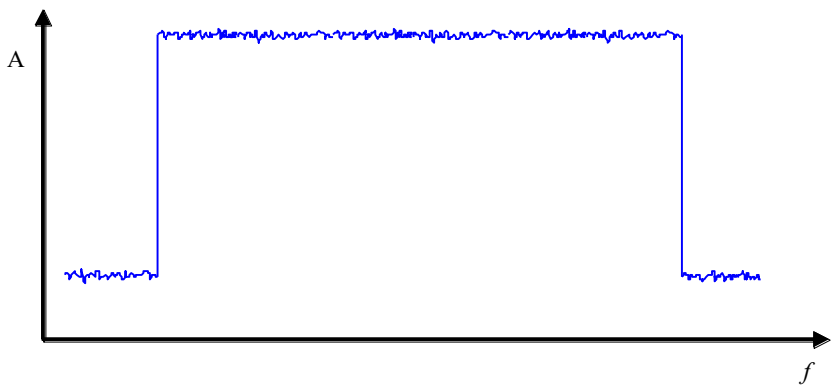
$$40\,902 \text{ bits} / 0.9 \text{ ms} = 45.447 \text{ Mbit/s}$$

Because the input data is spread over so many carriers, the system is very robust against frequency-selective fading and interference. Even if several carriers are unusable, data from the remaining carriers are still decidable.

If intelligent forward error correction (FEC) is applied, the receiver may still be able to reconstruct the whole symbol.

FIGURE 7-21

OFDM spectrum (principle)



Spectrum-6.6-18

The low symbol rate allows introducing a relatively long "guard interval". This is additional time in front of each symbol where information is repeated. The receiver can wait for the guard interval to pass before it starts the decoding process. If echoes from multipath reception arrive at the receiver before the guard interval has passed, they can improve the reception by adding up to the direct signal.

If the input data has a regular pattern, situations may arise where all (or at least many) of the carriers have equal phase and amplitude. Due to the high number of carriers in the ensemble, this would result in extremely high peaks of the total level to be transmitted. The output stages of an OFDM transmitter would have to be dimensioned for this peak level, whereas the average level affecting the coverage would be much lower.

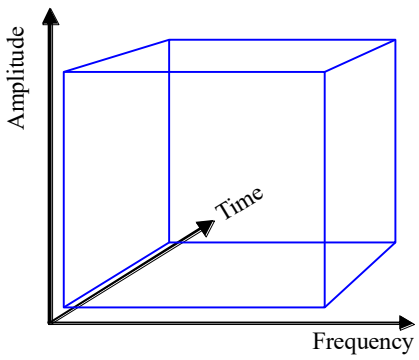
To prevent this from happening, the data stream is coded before transmission in a way that the resulting signal is always noise-like. The abbreviation for such systems is then COFDM for coded orthogonal frequency-division multiplex.

7.6.4 Spectrum access methods

The total capacity of a transmission channel can be symbolized as a cube in a three-dimensional Cartesian diagram like in Fig. 7-22.

FIGURE 7-22

Capacity of a transmission channel



Spectrum-6.6-19

The amount of information that can be transmitted is limited by three parameters:

– *Time:*

It is quite obvious that the more time available, the more information can be transmitted.

– *Frequency or bandwidth:*

The digital modulations presented all have a dependency between symbol rate and resulting RF bandwidth. So, more bandwidth availability allows modulation with a higher symbol rate and transmission of more useful data (bits/s).

– *Level or signal-to-noise and signal-to-interference ratio:*

If transmitter power is increased, improving the signal- to-noise or signal-to-interference ratio at the receiver, a higher modulation scheme that combines more bits per symbol (e.g., 64-QAM instead of 16-QAM) can be used. This also allows more useful bits to be transmitted at the same time.

In many practical systems, more than one user (or station) needs access to the transmission channel and its resources. Example: a cellular phone system where many persons want to telephone at the same time within the range of a base station.

The optimum usage of the channel capacity would be if the cube in Fig. 7-22 is completely filled without gaps. However, the system has to be organized in a way that multiple users can have access to the resources. The spectrum access methods to organize this are called multiple access modes.

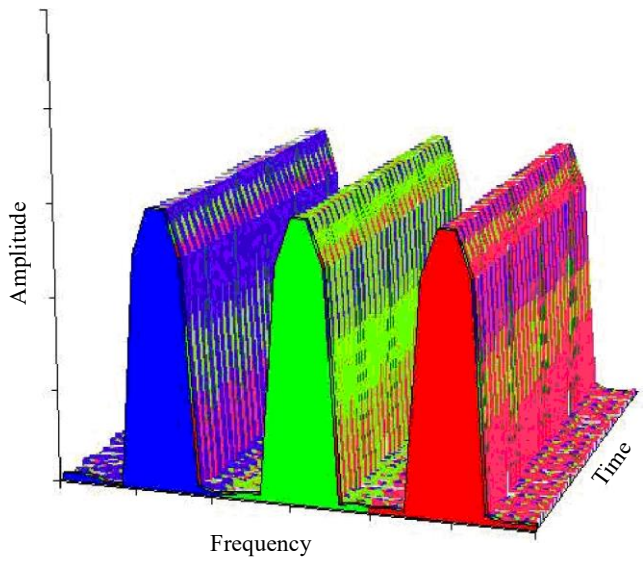
7.6.4.1 Frequency-division multiple access

Frequency-division multiple access (FDMA) is the simplest multiple access method and works also in analogue systems. Each user gets a different frequency on which he can use a certain part of the available spectrum continuously. The principle is illustrated in Fig. 7-23.

Because the selection filters of real receivers are not rectangular, a certain frequency spacing has to be maintained between the emissions of each user. Due to this requirement, there are “gaps” in the frequency domain that cannot be used for data transmission. The capacity cube of the transmission channel is not fully used.

FIGURE 7-23

Frequency-division multiple access



Spectrum-6.6-20

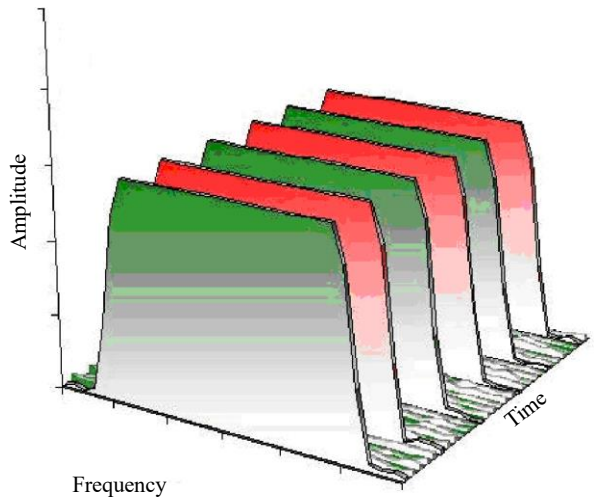
7.6.4.2 Time-division multiple access

Digital transmission has the advantage that the data can often be transmitted faster than the data source supplies it. In our example of the cellular phone system, continuous speech is digitized and split in time block of a certain length. If the transmission speed permits, data in these blocks can be transmitted in bursts, leaving unused time in which other users can transmit their data. So, this system divides the available time among the users, hence the name "time-division multiple access" (TDMA). Each user transmits his data in so-called "time slots", using the full bandwidth of the transmission channel. Figure 7-24 illustrates this principle.

If one of the users is far away from the common receiver (e. g. base station), his signal will arrive relatively late due to the limited speed of light and his emission may reach into the next time slot belonging to a user that is close to the common receiver. To avoid interference, guard times have to be inserted during which no user is allowed to transmit. Therefore, there will be "gaps" in the time domain where no data can be transmitted. So also, with TDMA, the capacity cube of the transmission channel is not fully used.

FIGURE 7-24

Time-division multiple access



Spectrum-6.6-21

7.6.4.3 Spread spectrum

FDMA and TDMA signals are generally susceptible to interference and therefore require time or frequency coordination between users. Spread spectrum signals are much less susceptible to interference and are often described as power-sharing signals. Multiple spread spectrum signals may simultaneously occupy the same spectrum.

Spread spectrum signals are created when a narrowband signal is modulated to occupy a larger bandwidth (spreading). As the spreading process does not increase power, power spectral density is decreased, making non-coherent signal detection more difficult. For example, the signal will be harder to observe in a power-spectrum measurement. The effects of interference from other signals are minimized in the spread-spectrum receiver when the signal is de-spread. The two most common techniques for creating a spread spectrum signal are frequency hopping (FHSS) and direct-sequence (DSSS).

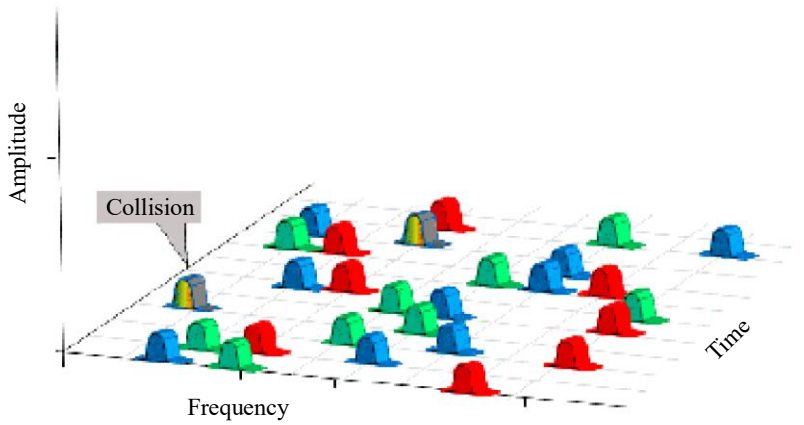
7.6.4.3.1 Frequency hopping spread spectrum

As the name implies, frequency hopping spread spectrum (FHSS) signals are created by periodically changing the transmission frequency. Receivers have to know, or recover, the timing and frequency hopping pattern to demodulate the signal. To minimize interference, different radios will have different frequency-hop sequences or will be at different phases in a long sequence. The hop sequences may not be coordinated or time synchronized between transmitters resulting in occasional collisions as indicated by the higher power rainbow spectrums in the three-transmitter example illustrated in Fig. 7-25. Error correction codes are typically used to

recover data lost during these brief periods of interference. Because the signals are harder to detect, and are more robust against interference, FHSS signals are often used in military applications. FHSS signals are also found in unlicensed spectrum where coordination between users is difficult. Coordinated frequency hopping is also part of the Global System for Mobile communications (GSM) cellular standard.

FIGURE 7-25

Frequency hopping spread spectrum



Spectrum-6.6-22

7.6.4.3.2 Direct sequence spread spectrum

Direct sequence spread spectrum (DSSS) signals are broadband signals created from narrowband signals by modulating a low-data rate sequence or modulation with a higher data-rate sequence or modulation. For example, a low-rate data sequence may be combined with a high-rate sequence using an exclusive OR (XOR) function. Alternatively, a low-rate binary phase shift keying (BPSK) modulation might be modulated with a high-rate QPSK modulation using a complex multiplication or mixing operation. The binary sequence used for the higher-rate sequence or modulation is often referred to as a spreading code, scrambling code, or key. The spreading code may be long or short and may be a specialized sequence such as a Barker code, or may be a more general sequence obtained from a pseudo-random number (PRN) generator.

The de-spreading process in the receiver recovers the original narrowband signal. Other unwanted signals will be spread by the de-spreading process but are not completely removed and will appear as broadband noise in the receiver. Much, but not all of the interfering signal's energy is removed using narrowband filters (usually in the form of integrators). Figure 7-26 illustrates the power-sharing concepts of DSSS. In the Figure, TX1 is higher power. This results in higher levels of interference from TX1 in RX2. CDMA systems constantly adjust the transmitted power to balance performance amongst all system users.

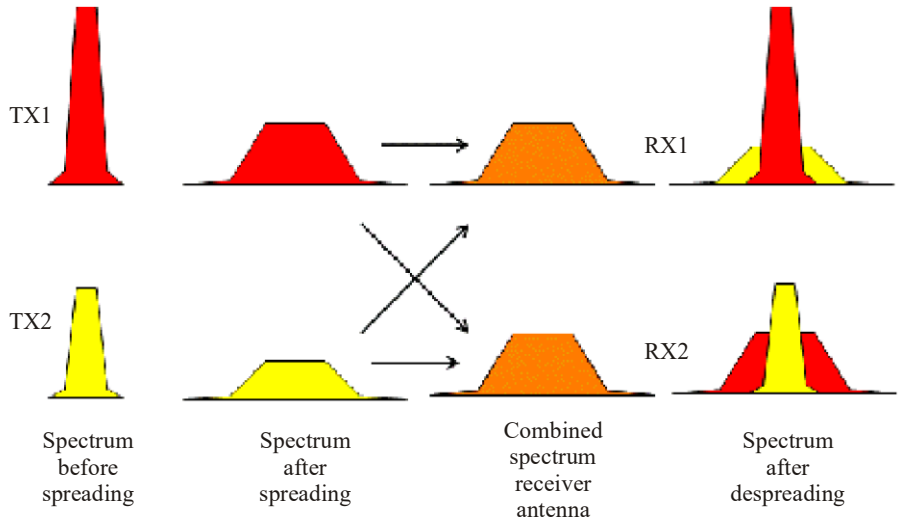
7.6.4.4 Code-division multiple access

In order to avoid unused "gaps" in the transmission capacity cube (see Fig. 7-22), the user data can be digitally "modulated" on to a so-called "key" which is a fixed bit sequence. This modulation is a logical "XOR" operation on each bit of the user data. As a result, instead of a "1", the key is transmitted, instead of a "0", the inversed key is transmitted. Figure 7-27 illustrates this principle with an example of a key that is 4-bit long.

The receiver operates in the same way: always groups of 4 bits (example) are compared with the key. The result is always "1111" or "0000". These 4-result bits are then "averaged" to form the actual output bit. This process is illustrated in Fig. 7-28.

FIGURE 7-26

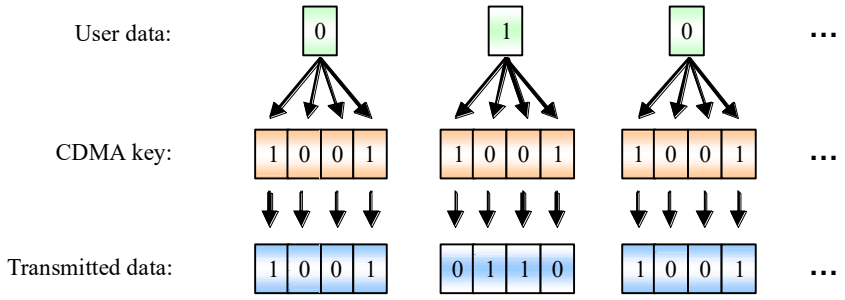
Direct sequence spread spectrum



Spectrum-6.6-23

FIGURE 7-27

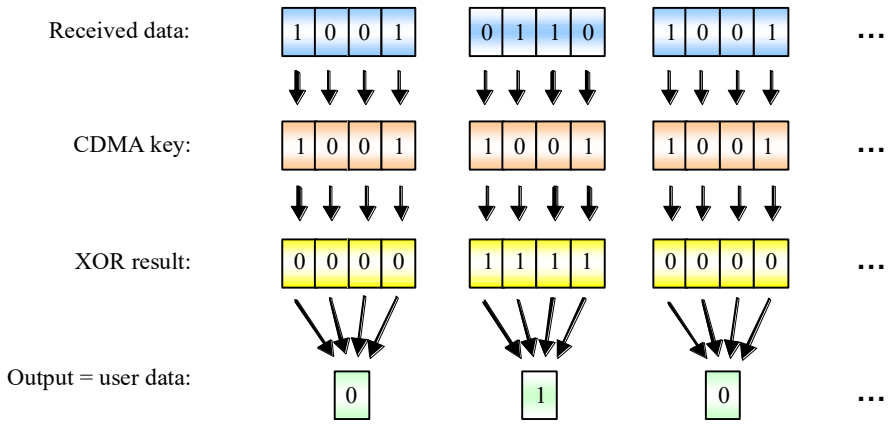
Digital modulation with a CDMA key



Spectrum-6.6-24

FIGURE 7-28

CDMA reception with correct key

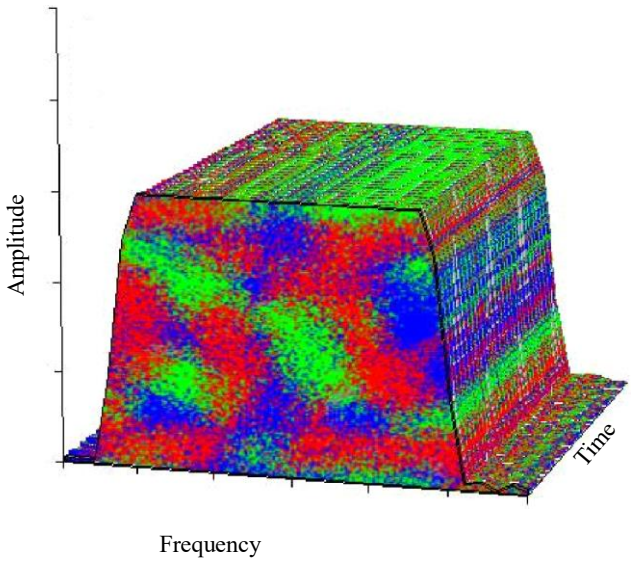


Spectrum-6.6-25

Because the amount of data to be transmitted is much higher (by the factor of the key length) than the user data, the transmission speed has also to be higher, resulting in much more required bandwidth. Our Example with a 4-digit key creates a data stream that is four times as fast as the user data stream. To transmit this amount of data with the same modulation parameters, the symbol rate has to be four times higher resulting in a four times wider bandwidth. If certain mathematical requirements are fulfilled by the keys, then the "redundancy" of user data at the receiver can be used to allow very high error rates before the signal is detected incorrectly. In such a system, up to four stations, each using a different 4-digit key, can transmit at the same time on the same frequency, and still the receiver is able to filter out the correct signal from all the others. This is made possible by designing the different keys in such a way that the XOR comparison with a block coded with any "wrong" key has equal numbers of "1" and "0", so that the integration over the whole block is in the middle between "0" and "1". A 4-bit sequence supports up to four data channels. Four 4-bit keys which meet the described requirements are: 1111, 1100, 1010, and 1001. Four data streams spread with these keys are summed together for transmission. The received signal is separated back into four independent data streams in the receiver using the same keys to de-spread the composite signal. The gross spectrum efficiency of CDMA is better than FDMA and TDMA, because the transmission capacity cube has no gaps. This is illustrated in Fig. 7-29.

FIGURE 7-29

Code-division multiple access



Spectrum-6.6-26

In the case where signals from multiple users can be controlled so as to arrive at a receiver with proper time-alignment, it is possible to eliminate the mutual interference between users through the use of orthogonal spreading codes, or keys. Proper time alignment is required as the spreading codes are only orthogonal (non-interfering) when time aligned. With orthogonal spreading codes, users are not sharing power, but are instead sharing a code space, hence the term "code-division multiple access" (CDMA). Cellular CDMA systems use both orthogonal spreading codes to separate data streams (traffic and control channels) in a sector, and non-orthogonal (cover) codes to separate base stations and mobiles.

As cellular systems use non-orthogonal spreading codes to separate transmitters (base stations and mobiles), optimal performance requires that signals from all users arrive at the receiver with nearly the same field strength. In a real environment like in our cellular phone network example, this is not possible unless all transmitters are constantly adjusting their transmit power according to the information given to them by the common receiver (base station). This requires a fast organization channel that can occupy a considerable part of the available data rate, reducing the net rate for user data. Once the signal from a single transmitter has been

isolated by first de-spreading with the non-orthogonal cover code, the independent data channels can be subsequently separated and recovered using the orthogonal codes (keys).

7.6.4.5 Spatial multiplex (SDMA) and spatial channels

Location is a fourth dimension which can extend the channel capacity model in Fig. 7-22. Two obvious and simple examples come from traditional cellular systems where spectral resources are re-used at multiple locations according to a frequency, or code re-use pattern, or where directional antennas are used to allow re-use at different angles (sectors).

In reflective environments with significant multipath, it is possible take advantage of the multipath to create multiple spatial channels which can then be used to increase data capacity, increase robustness, or to support more users.

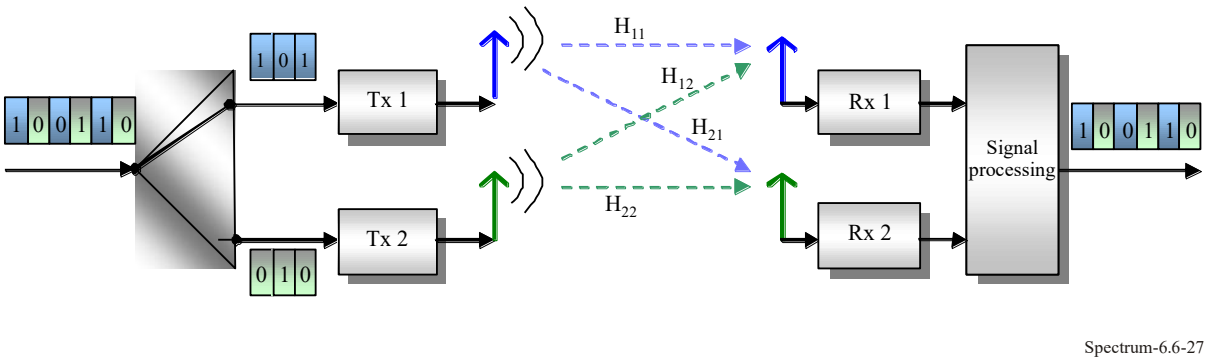
Close-spaced antenna arrays combined with gain and phase modulation on each antenna allow maximum energy to be delivered to one location, while minimizing it at another. This is often referred to as spatial-division multiple access (SDMA). A simple example would be beam steering and null steering, which is effective in non-reflective environments. One user's beam would be pointed in the direction of that user, while nulls would be steered to prevent the first user's signal from interfering with other users. SDMA also works in reflective environments, though the radiation pattern is much more complicated, and knowledge of the channel is required to create the steering vector. The steering vector is the collection of magnitude and phase adjustments applied to the signal fed to each antenna.

Closely related to SDMA is multiple input, multiple output (MIMO) which refers to a system employing multiple transmit antennas and multiple receive antennas. MIMO radio systems use wide-spaced antenna arrays to minimize correlation between antennas. The wide spacing generally precludes beam-forming. Wide antenna spacing and other factors such as polarization can increase the number, or quality of the spatial channels.

The theoretical increase in the capacity of a MIMO system is determined by the number of transmit and receive antennas. A 2x2 MIMO system, as illustrated in Fig. 7-30 could theoretically have as much as twice the capacity of a radio system employing only one transmit and one receive antenna; a 3x3 MIMO system could have triple the capacity.

FIGURE 7-30

Multiple Input, Multiple Output



MIMO techniques are included in IMT-2020 services such as 5G, LTE, WiMax and WiFi (802.11n) standards.

The concept is similar to running a second pair of wires to double the capacity of a cable. Of course, wires generally have good isolation between cable pairs, whereas in MIMO radio systems, the received signal at each receive antenna is a linear 1combination of the transmitted signals. This would be similar to a cable with significant amounts of crosstalk between wire pairs. In a MIMO system, the cross-talk terms, H_{12} and H_{21} illustrated in Fig. 7-30 may be non-zero without causing a loss of capacity. What is important is the condition of the channel matrix [H]. For the original data streams to be recovered, the multipath has to cause the received signals Rx1 and Rx2 to contain significantly different linear combinations of the Tx1 and Tx2 signals. For

example, if the two received signal streams are Rx1 = (Tx1+Tx2) and Rx2= 2*(Tx1-Tx2), then Tx1 can be recovered by summing the two received signals using 0.5*Rx1 + 0.25*Rx2. Tx2 can be similarly recovered. Alternatively, if the MIMO system is in a non-reflective environment, both receivers could see the same linear combination of signals (e.g. Rx1=Tx1+Tx2 and Rx2=0.9*(Tx1+Tx2)). In this situation, while the two received signal levels may be different, there is only one spatial channel. Tx1 and Tx2 cannot be independently recovered through any linear combination of the received signals.

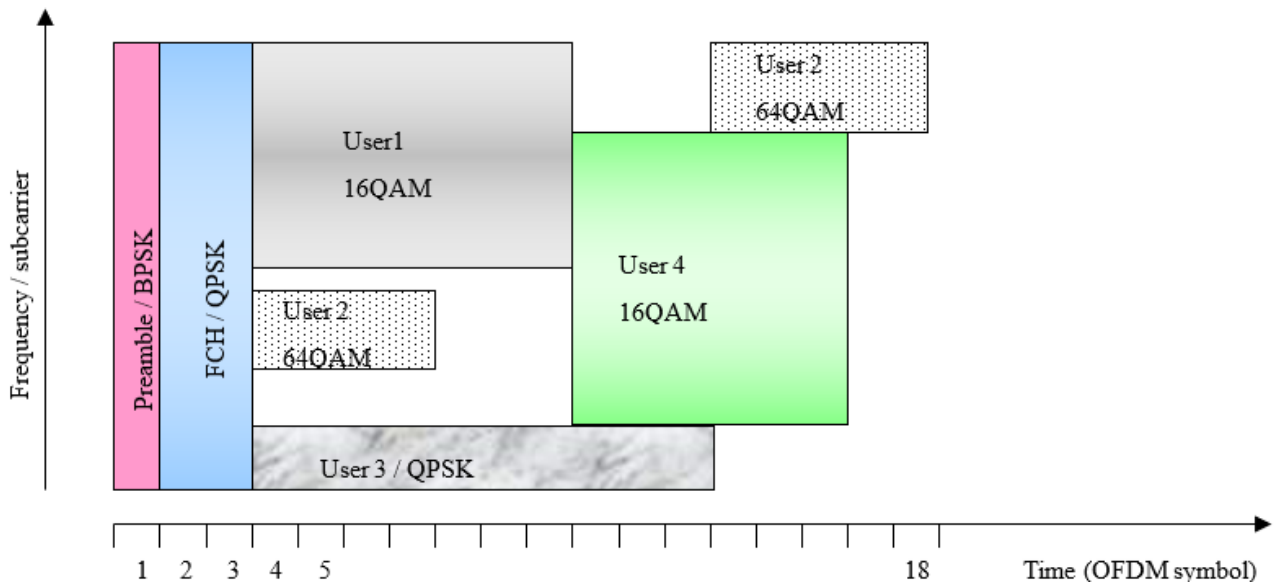
7.6.4.6 Orthogonal frequency division multiple access

Orthogonal frequency division multiple access (OFDMA) may be regarded as a specific case of OFDM modulation, but it is mainly regarded as a spectrum access method. Modulation is based on OFDM principles where subcarriers are modulated with a part of the input data bits. In OFDMA, however, subcarriers are grouped into Resource blocks (RBs). Each RB can be switched on and off and even modulated independently. Apart from covering only a few subcarriers, an RB also has a limited transmission time. Usually this is a few symbols, but can be as short as one OFDM symbol.

Depending on the traffic demand and number of users, a Scheduler assigns RBs and transmission times to each user. This is a most flexible way to divide the available data rate among different users. Figure 7-31 shows a simplified example of this principle.

FIGURE 7-31

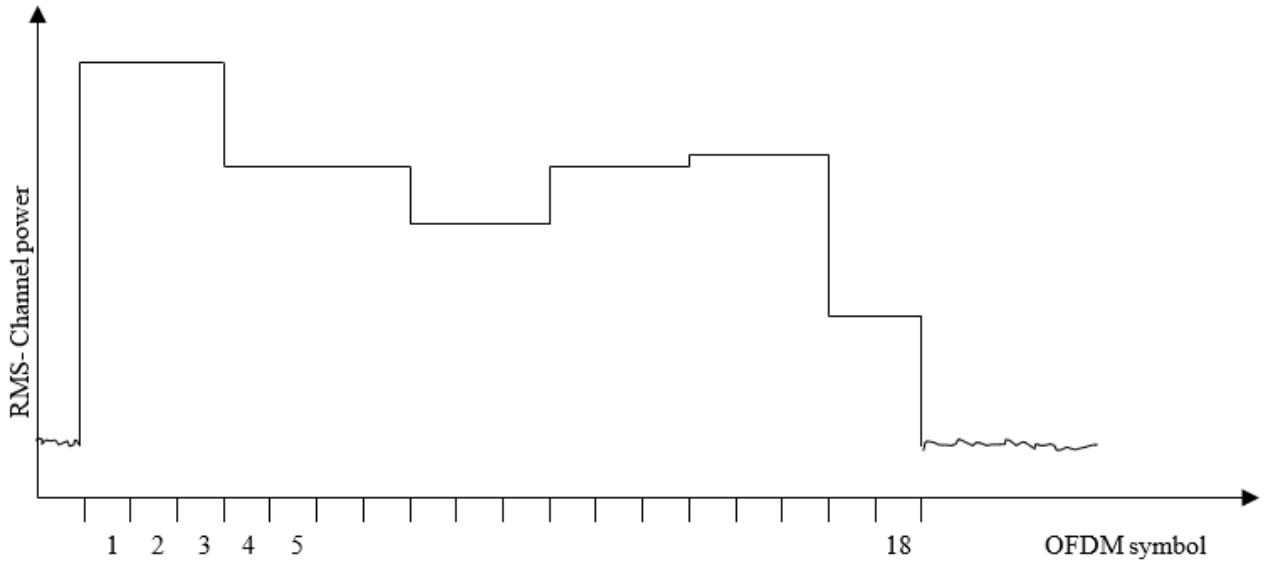
Simplified example of an OFDMA signal in frequency and time domain



The resulting spectrum, however, is highly dynamic. The total channel power also varies depending on how many RBs are active at a time. Using the example above, Fig. 7-32 shows the momentary channel power of the OFDMA signal in Fig. 7-31 over time.

FIGURE 7-32

Channel power vs. time of the signal in Fig. 7-31



This dynamic behaviour both in frequency and time domain makes measurements of OFDMA signals specifically challenging. See § 6.3 of Chapter 6 for details on measurements. Among other systems, OFDMA is used in 4G / LTE and 5G / NR public mobile networks.

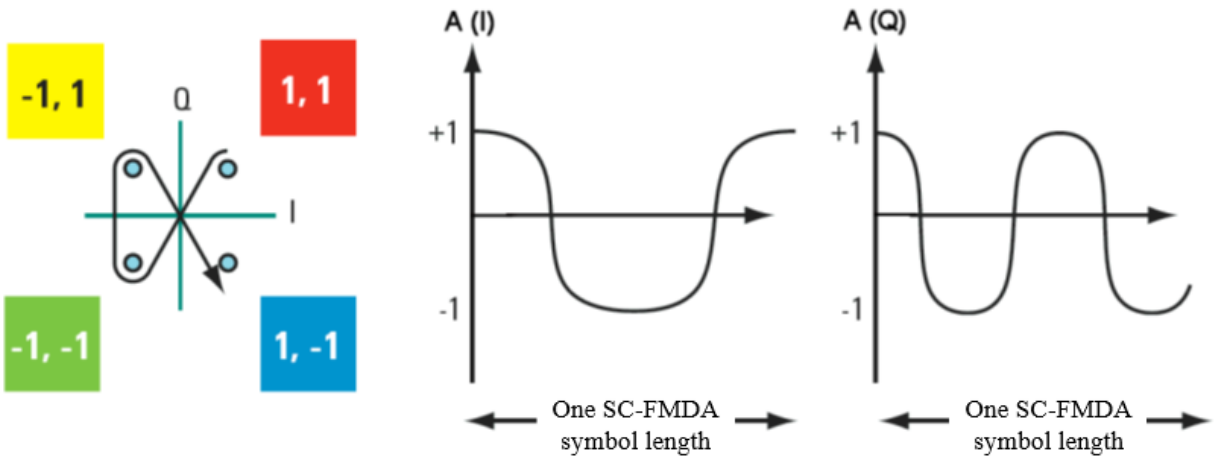
7.6.4.7 Single carrier frequency division multiple access

Single carrier frequency division multiple access (SC-FDMA) could be regarded as a mixture between OFDM and single carrier modulation. OFDM modulations have a relatively high peak-to-average ratio (CREST factor) in the order of 10 dB. Transmitters have to be capable of transmitting the high peaks while the average level (which is important for the coverage range), is only 1/10 of that power. On the other hand, OFDM is extremely resistant against narrowband interferers, and it can even use multipath echoes to increase reception by introducing a guard interval. SC-FDMA combines the advantages of a guard interval while still having CREST factors in the order of 3 dB. This is done by combining a certain number of user bits from several OFDM carriers and modulating them on a single carrier. The guard interval is then added only after the whole group of data has been modulated.

Figure 7-33 describes this principle with an example in which data from four users (or logical channels) are transmitted. Each symbol contains 2 bits. In OFDMA using QPSK subcarrier modulation, 4 subcarriers would be needed. In SC-FDMA, the symbols are modulated one at a time onto a single carrier, also using QPSK. The symbol rate of the single carrier is 4 times higher than in OFDM, occupying the same bandwidth as an equivalent OFDMA. However, data from each user is transmitted only once every four symbols. This allows the guard interval to be inserted after the data from four users are transmitted.

FIGURE 7-33

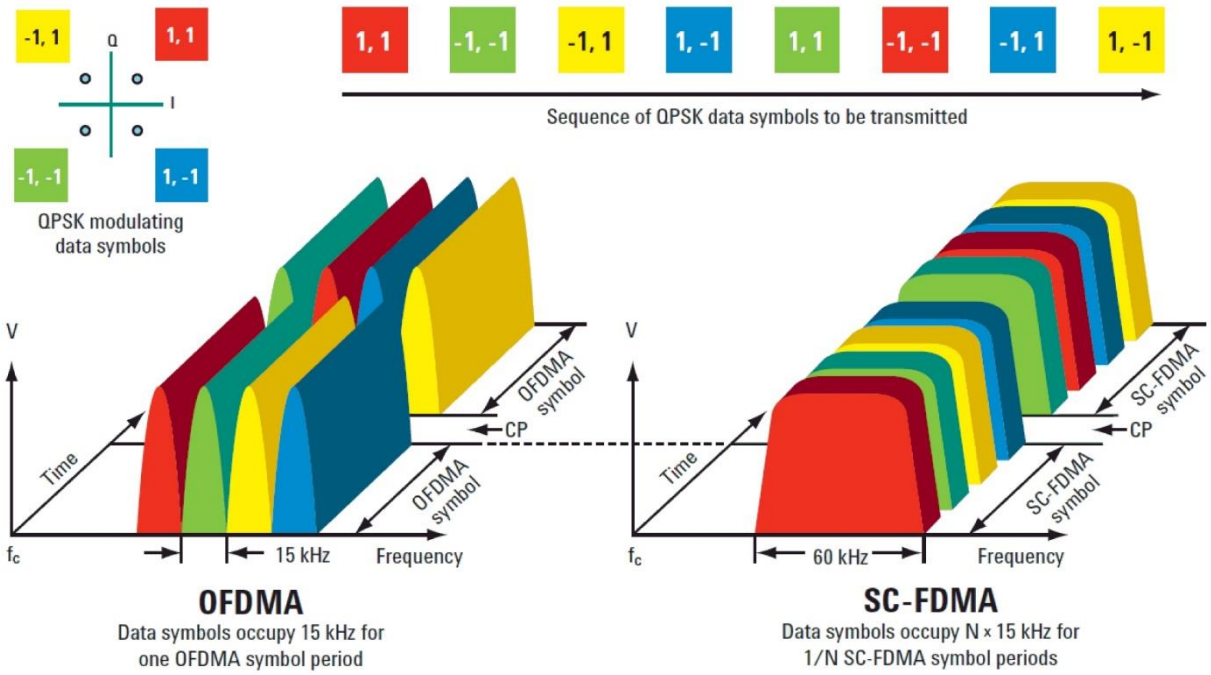
Example of SC-FDMA with 4 users/channels using QPSK modulation



This time signal is then transferred via DFT to the frequency domain, resulting in 4 sinewave carriers with different amplitudes. These sinewaves are shifted to position in the channel by multiplication. The data from the next 4 users (or logical channels) is modulated in the same way and shifted to a frequency above the previous one. The result is an OFDM-like signal consisting of ¼ of the subcarriers of an equivalent OFDM. Other than with direct OFDM, the amplitudes of the SC-FDMA signals are not arbitrary and therefore may not add up to very high peaks. The guard interval is only transmitted after every SC-FDMA symbol length, equal to the rate of a direct OFDM. This way, the advantage of resistance against multipath reception can be maintained. Figure 7-34 illustrates the differences of OFDMA and SC-FDMA for the chosen example.

FIGURE 7-34

Comparison of SC-FDMA and OFDMA



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CARLSON, A. B. [1986] *Communications Systems*. McGraw Hill.

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ITU-R Recommendations and Reports

NOTE – In every case, the latest edition of the Recommendation and Report is encouraged to be used.

Recommendation ITU-R SM.328 – *Spectra and bandwidth of emissions*

Recommendation ITU-R SM.1541 – *Unwanted emissions in the out-of-band domain*

Report ITU-R SM.2048 – *Use of the x-dB bandwidth criterion for determination of spectral properties of a transmitter in the out-of-band domain*.

7.7 Fast Fourier transform

7.7.1 Basics

Whenever a signal is to be transformed from time domain into frequency domain, a mathematical method called Fourier transformation can be used.

This method is based on the fact that any real signal, irrespective of its waveform, can be constructed by adding up a number of sine wave signals of different amplitudes, frequencies and phases. Consequently, any received time signal can be broken up into a number of different sine waves in the frequency domain.

Whereas the Fourier transform method at first sight seems to be the best way to solve all signal analysing problems, there are certain restrictions as well as measurement uncertainties which originate from both the necessary analogue-to-digital conversion process and the Fourier Transform itself. To understand these restrictions, a short look into the principles is necessary.

Jean Baptiste Joseph, Baron de Fourier, proved in 1822 that each time variable phenomenon can be seen as an addition of a number of sinusoidal frequency components, each with their own amplitude and phase.

He presented this in Fourier series for periodic and band limited signals, presented in a common form in equation (7-29).

$$x(t) = \sum_{k=-N}^{N} C_k \cdot e^{j\omega_k t} \tag{7-29}$$

The Fourier series are only valid for periodical signals that have a mutual harmonic relation with each other, but in practice a non-periodical signal is much more common. The number of components that composes the waveform becomes infinite. This changes the equation to an integral form as:

$$x(t) = \int_{-\infty}^{\infty} X(\omega) \cdot e^{j\omega t} d\omega \tag{7-30}$$

Equation (7-30) is sometimes called the ‘forward transformation’. The inverse function – the ‘backward transformation’ – of that equation is given by:

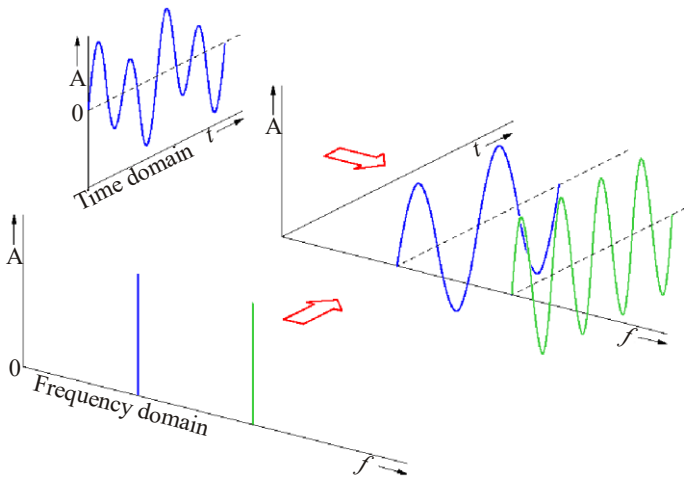
$$X(\omega) = \int_{-\infty}^{\infty} x(t) \cdot e^{-j\omega t} d\omega \tag{7-31}$$

The combination of both equations is called the DFT pair.

This last equation makes it theoretically possible to calculate the complex spectrum of a continuous signal in the frequency domain with the use of its time domain waveform.

FIGURE 7-35

Time and frequency domain



Spectrum-6.7-01

Unfortunately, the method is not suitable for the calculation of the spectrum of arbitrary signals. While the signals are continuous and the integration should be carried out from minus infinity to plus infinity, it would require an infinite computing capacity. The problem can be resolved by making the signal discrete in time by sampling and introducing the discrete Fourier transform (DFT). A signal with limited bandwidth can be characterized by its samples taken in $n \cdot T_s$ time instances,

where:

n : integer number running from 0 to $N - 1$,

T_s : period of sampling

N : total number of the samples (see § 7.7.2).

Applying the DFT algorithm to these N time domain samples results in N samples in the frequency domain, hence the term of an 'N-Point DFT'.

The formula of the DFT is:

$$X[k] = \frac{1}{N}\sum_{n=0}^{N-1} x[n] \cdot e^{-j2\pi kn/N} \tag{7-32}$$

The inverse of it is:

$$x[n] = \sum_{k=0}^{N-1} X[k] \cdot e^{j2\pi kn/N} \tag{7-33}$$

$X[k]$ denotes the value of the spectral component at the frequency of $k \cdot f_0 = {}^{k}/_{N} \cdot T_s$, while x[n] denotes the time domain sample at the instance of $n \cdot T_s$.

The exponential term can be compared to the frequency sweep of a swept spectrum analyser's local oscillator with the main difference that all frequencies are analysed in parallel at the same instant of time. A DFT can process samples in blocks of arbitrary length. However, if the block length is a power of 2, the calculation can be performed in a much faster way. This is called Fast Fourier transform or FFT.

Before the mathematical Fourier transform can be applied, a certain amount of data representing the waveform has to be stored in memory as a so-called "time record" or "frame". The minimum duration of this time record is the period of the lowest frequency to be processed. The time this takes is called collection time or acquisition time. Then the whole waveform is analysed in one go and mathematically converted into a series of sine waves of different amplitudes, frequencies and phases. The result is an analysis of the whole spectrum part at a certain point in time.

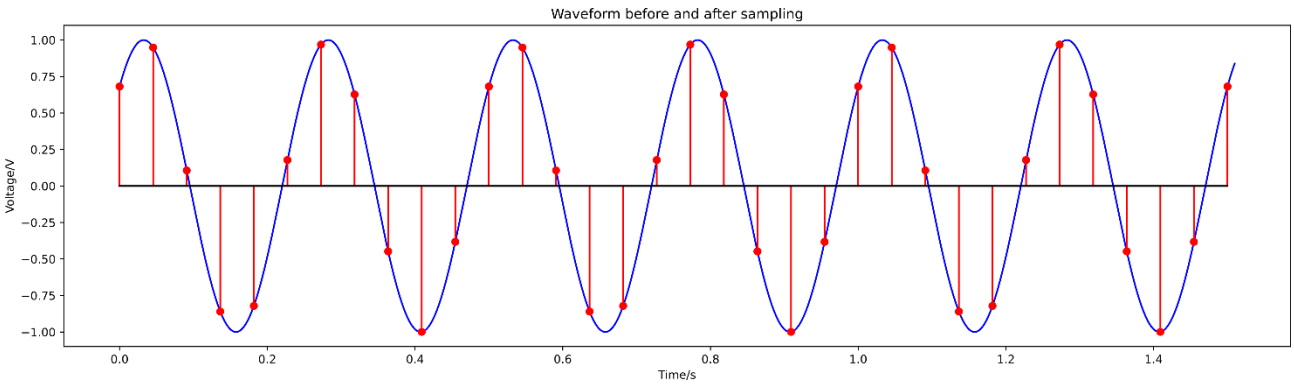
The output of the Fourier transform is complex valued regardless of whether the input time waveform is real or complex (e.g. real and imaginary, or *I* & *Q*). If the input waveform is real-only, the spectrum result will be conjugate symmetric. The power spectrum from the Fourier transform result is the magnitude-squared value of each frequency point (bin).

7.7.2 Analogue to digital conversion, sampling

Being a mathematical process, the Fourier Transform is best performed by a digital signal processor (DSP), which basically is a computer with optimizations for lots of fast multiplications and additions. For this purpose, the time signal has to be present in digital form. This is done by an analogue-to-digital converter (ADC).

FIGURE 7-36

Analogue to digital conversion



An analogue signal is converted into a digital signal by taking samples of its current amplitude during a certain period of time. Nyquist's theorem states that the sampling frequency has to be more than twice the bandwidth – the highest frequency present – of the waveform to be sampled:

$$f_s > 2b$$

This is called the Nyquist frequency as applied to real signals. For complex signals, such as can be obtained with two ADC's sampling the output of an IQ demodulator, the sample rate has to be greater than the bandwidth of the signal ($f_s > b$). Information is not lost because with complex signals, there are two values per sample, so the sample density is the same as in the case of real signals with one value per sample, but at twice the rate.

On the lower end of the spectrum, one has to consider that the lowest frequency component to be measured also needs to be recorded by a suitable long recording time: if a signal contains a 10 Hz-component, then the record has to be at least 0.1 seconds long to resolve at least one cycle.

The output of the ADC is a bit stream in which a number represents the amplitude of the original signal at the time of each sample.

The ADC's output is a complete representation of the input signal, if the sampling frequency is high enough. The FFT divides the sampling frequency into N slices, where N is the number of FFT points (bin). Thus, the binwidth –the spectral resolution of one FFT point– is given by f_s/N.

The accuracy of this digital representation depends on the number of bits reserved for each amplitude value. Typical ADC resolutions are in the range of 14 to 18 bits, resulting in up to 262.144 different amplitude steps. Although the discrete amplitude values cannot accurately represent the original signal, the error due to this effect can be minimized by proper selection of the spacing between two steps (narrow spacing at low, wide spacing at high amplitude values). This way, the dynamic range of the digitized signal can be better than 100 dB.

Frequencies higher than twice the sample rate would be "undersampled", resulting in additional frequency components ('alias spectra') in the digitized signals that are not part of the original signal. To avoid this error,

it is essential that the analogue signal is fed through a low pass filter placed before the ADC, called anti-alias filter.

In principle, the accuracy of the digitizing process is therefore only limited by the speed of the ADC unit. To analyse higher frequencies than the maximum speed of the ADC, the RF signal first has to be down-converted to a range that can be digitized.

7.7.3 Windowing

The need for windowing

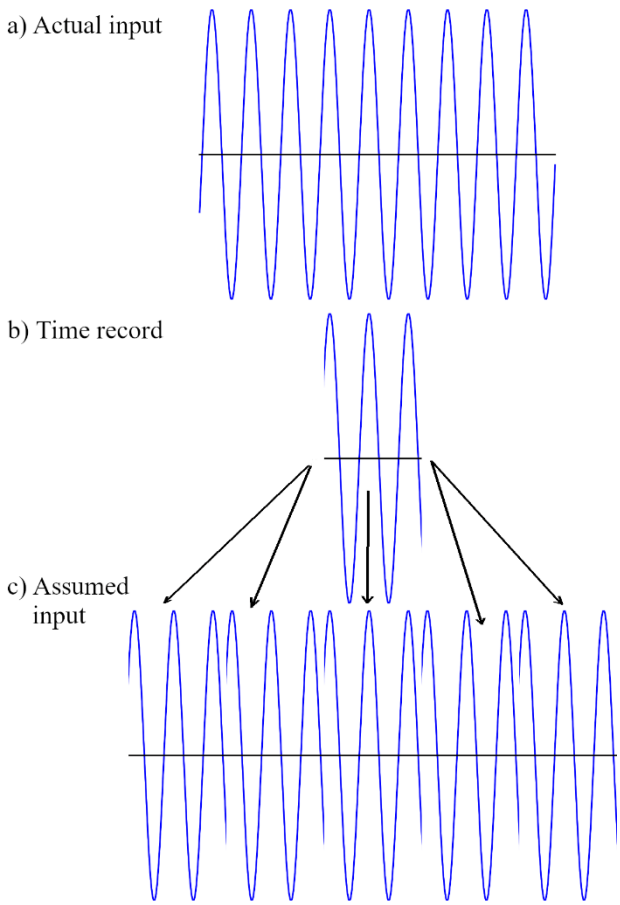
The FFT is computed over a finite time interval. If the collected signal is periodic within that interval, then the result is considered to be an accurate representation of the signal's spectrum. If the signal is not periodic within the interval, then the fundamental assumptions made in defining the Fourier Transform are no longer valid, and the resulting spectrum estimate will be less accurate. This can lead to spectral lines that are not present in the wanted signal, that just result from the limited number of available time due to the introduction of jumps and gaps in the (digitized) signal.

The FFT procedure implies that the collected signal is continuously present for an infinite time and that it is periodic within the time record. If the signal is not periodic, then there will be a discontinuity as shown in Fig. 7-37. While this signal is continuous, the time record used to compute the FFT contains 2.5 cycles of the sine wave, instead of the assumed integral number of cycles.

The FFT result can only accurately represent a finite set of integral frequencies such as 2 cycles, 3 cycles, etc. As there is not a 2.5 cycle coefficient, the result in this example will erroneously indicate energy at a number of integral frequencies.

FIGURE 7-37

FFT of a continuous sine wave signal



In most cases, the signal analyser is not synchronized to the signal source. For that, the start and end of the samples is random and have no defined start and end point. Window functions are used to improve the accuracy of the spectrum estimate by shaping the signal, minimizing the cutting effects (sudden changes) at the window edges.

Signals that fall completely within one time record appear to be periodic to the FFT. These signals are called self-windowing. To analyse them accurately with FFT, no extra windowing has to be applied (sometimes this is called applying a rectangular window): examples of this kind of signal are spikes occurring only once and digital burst signals, as long as the burst lies completely within the time record.

Implementation of windowing

It is quite obvious for continuous signals that the original waveform is altered due to the need for windowing, and always introduce a certain error. This error lies in the principle of the FFT-windowing and cannot be completely avoided. However, depending on the parameter to be measured (amplitudes, frequencies, phases), this error can be minimised by choosing an appropriate window function.

A window is a series of values that follow a specific function. These functions are always even and hence symmetric to the vertical axis as well as their values are real (not complex).

Generally speaking, the windowing has influence on the frequency spectrum in both frequency resolution and amplitude accuracy. The DFT/FFT can be depicted as a bank of parallel filters, each filtering out a frequency component. The window function is comparable to the impulse response of a resolution bandwidth filter in a spectrum analyser as it defines the corresponding frequency domain characteristics of bandwidth, shape factor and sidelobe (stopband) performance. In practical applications, the windows function is multiplied to the time samples before the FFT, which corresponds to a convolution in the frequency domain – and thus, the window acts as a filter. The length of the window is matched to the number of FFT bins. With that, the application of the window sequence $w[n]$ with length N to the input sequence $x[n]$ yields the windowed input sequence $x_w[n]$ as shown in equation (7-34):

$$x_w[n] = x[n] \cdot w[n] \quad \text{for } n=0..N\text{-}1 \tag{7-34}$$

The windowed DFT result $X_w[n]$ is finally obtained by feeding the windowed input sequence into the DFT equation (7-32):

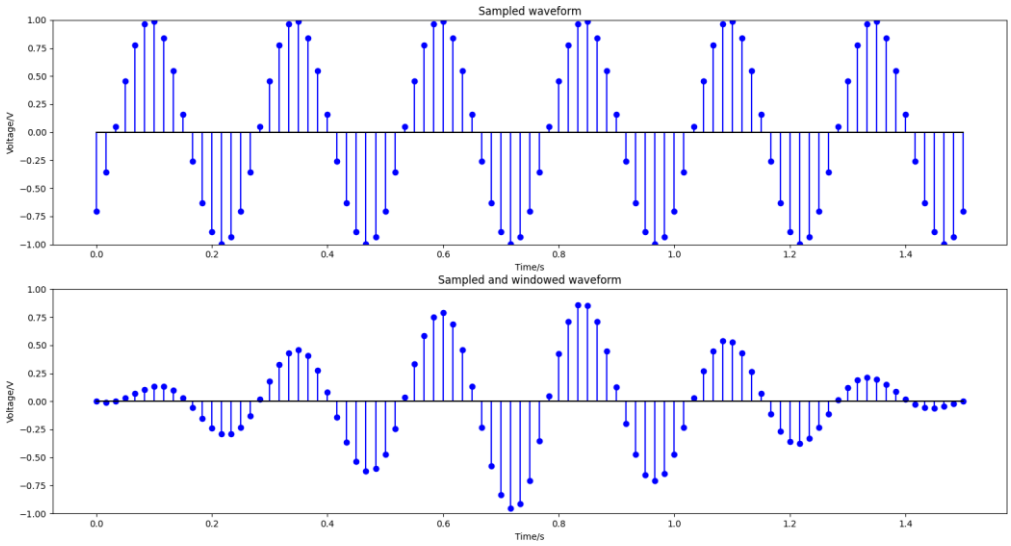
$$X_w[k] = \frac{1}{N}\sum_{n=0}^{N-1} x_w[n] \cdot e^{-j2\pi kn/N} \tag{7-35}$$

It is important to keep in mind that any sequence of samples is windowed, as the start and end of recording acts as a hard switch ($w[n] = 1 \; \forall \; N$). This implies a rectangular (boxcar) window.

Figure 7-38 gives an example of the effect that the windowing process has on the recorded samples: at the edges, the signal is smoothed. This dampens unwanted high-frequency components, but still broadens the spectral line of the carrier wave. This also leads to a diminished amplitude of the signal.

FIGURE 7-38

Windowing



Many different windows have been developed, each with their own specific properties. There is no single window type that is optimal for all cases. One always has to consider the kind of signal to be analysed (transient or continuous) and the aim of the measurement (emphasis on frequency resolution or amplitude accuracy) in order to find a window that offers the best compromise. The effects on the signal – amplitude loss, frequency resolution, sidelobe suppression, etc, can be looked up in literature.

FFT equipment used for spectrum monitoring often allow the user to select between different FFT windows. It is necessary to know the characteristics of the window functions implemented in order to select the appropriate one for the respective measurement task. Table 7-9 shows examples of windows commonly implemented in RF measurement equipment. Nonetheless, in most cases the general-purpose approach chosen by the instrument's manufacturer suffices in most of the times.

TABLE 7-9

Examples of common FFT window functions

Window function	Application
Rectangular	Used for transient signals that lie completely within the time record
Hann	High frequency accuracy
Blackman-Harris or Flattop	High amplitude accuracy, high dynamic range and noise suppression
Gaussian	Compromise between frequency and amplitude accuracy (depending on shape factor)
Kaiser	Adjustable, trade-off between frequency resolution and high sidelobe suppression

7.7.4 FFT implementations, overlap processing

The FFT can be viewed as a parallel bank of resolution bandwidth (RBW) filters. As the spectrum is estimated at all frequencies simultaneously, the FFT produces a self-consistent spectrum estimate when applied to highly dynamic waveforms.

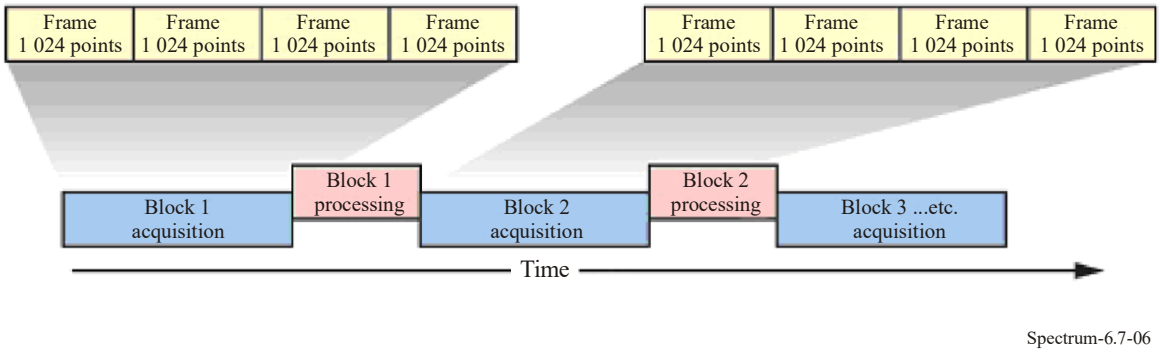
The parallel nature of the implementation also provides faster spectrum measurements for narrow RBW's when compared to a swept spectrum analyser that can only measure one frequency at a time. It also means that there are many analyser detectors (e.g. Peak, R.M.S., Average, …) in parallel.

If the FFT is implemented in such a way that the FFT analyser cannot collect data while computing the FFT, then the receiver is "blind" during the FFT calculation, so there is no continuous reception and short time

signals may be lost. To overcome this limitation, different techniques have been developed in modern FFT analysers. One method is to collect multiple time records first and compute all the FFTs afterwards in one block (see Fig. 7-39).

FIGURE 7-39

Block acquisition

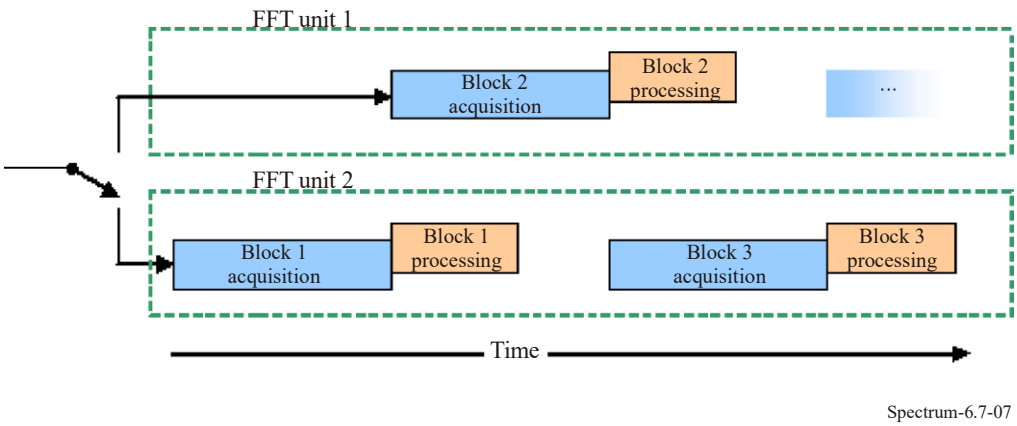


During the longer computation time, reception is discontinued, but if the acquisition can be triggered to the signal of interest, and if the available memory allows long acquisition times, continuous reception at least over the time period of interest is possible.

One method to provide continuous reception is to implement two acquisition and FFT computation units that take turns in the processing of the signal (see Fig. 7-40).

FIGURE 7-40

Continuous reception with two FFT units



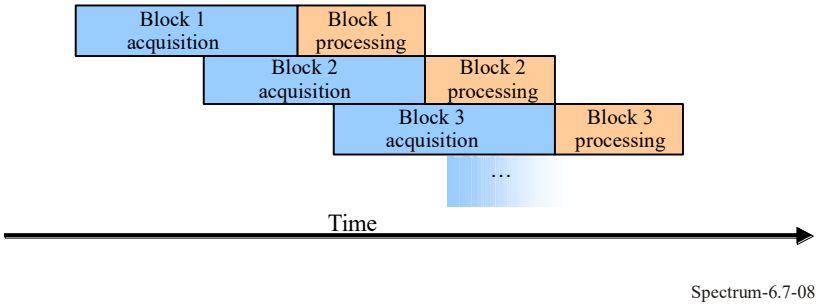
While not obvious, there are still gaps in the processing in Fig. 7-40. This occurs as the window function weights the waveform to zero at the beginning and end of each acquisition block. This problem can be resolved using overlap processing as described below.

The FFT is not immune from time-frequency resolution trade-offs. The number of frequency lines in the FFT spectrum is equal to the number of samples in the time record. The minimum duration of the time record is 1/frequency resolution. To increase frequency resolution, the length of the time record has to be increased (thereby losing time resolution), and vice versa.

Some FFT analysers can minimize this limitation by overlapping time records (see Fig. 7-41) thus improving visual representation of short pulses. This method is also known as short time FFT, sliding window FFT or overlap processing. A similar time-frequency resolution trade-off exists in swept spectrum analysers where sweep time has to be increased as the resolution bandwidth is decreased.

FIGURE 7-41

Overlapping time records



7.7.5 Range of applications

FFT techniques are commonly used in spectrum analysis and spectrum monitoring. The following enumeration is a non-exhaustive list of parameters which can be measured by using FFT techniques.

– Level.

– Frequency.

– Occupied bandwidth (x-dB method and β/2-method).

– Spectrum occupancy (spectrograms and frequency channel occupancy).

– Detection of short time emissions.

– Detection of signals below the noise floor.

For more details, please refer to the relevant sections in Chapters 4 and 5.

Since the complex FFT gives both amplitude and phase information, wideband direction finders can use FFT algorithms to make bearings on multiple signals at the same time. Another example is the Goertzel algorithm, an FFT for one frequency point. If the FFT is considered as a bank of filters the Goertzel algorithm is just one of them. Applications are the dual tone multiple frequency (DTMF) and the continuous tone-coded squelch system (CTCSS) decoders or other tone-decoders, filters in receivers, filters for FSK demodulators etc. All the properties (resolution, dynamic range) of the FFT apply to these applications. The reason for using FFT algorithms is not always better performance. FFT enables a seamless processing of a given spectrum over time which is not possible with an analogue sweeping process. The availability of cheap DSPs makes FFT-based products cheaper to manufacture than their conventional analogue counterparts. Although excellent products are available a careful review of equipment is always recommended.

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7.8 Planning and optimization of spectrum monitoring networks

7.8.1 Introduction

The planning of spectrum monitoring networks, whether global, comprising many monitoring stations, or local, comprising only a handful of stations, involves determining the optimal siting of fixed stations while considering their interaction with one another and with mobile stations. The term "monitoring station" refers both to a fully equipped station performing all the monitoring functions referred to in Chapter 5, and to remote automatic stations performing only direction finding.

The goal of planning a spectrum monitoring network is to cover the greatest possible land area using the smallest possible number of stations. The planning of new and optimization of existing spectrum monitoring networks is of great economic significance considering that the cost of the monitoring system generally accounts for the bulk of the cost of any national spectrum management system. Optimization of a spectrum monitoring network can result in considerable financial savings.

Once a station has been optimally sited within the network by means of calculations for which the methodology is shown below, that station has to be specifically customized to the locality and surrounding features, in accordance with the provisions of § 2.5 of Chapter 2. Should that customization require that the station be sited other than in the calculated location, it may prove necessary to recalculate the network parameters in view of the new configuration of stations.

7.8.2 Principles for the planning and optimization of spectrum monitoring networks

The planning of a new or optimization of an existing spectrum monitoring network may be performed by calculating the corresponding coverage zones with reference to the two tasks for which spectrum monitoring is typically used [Kogan and Pavliouk, 2004].

The first of those tasks fulfils the functions described in §§ 5.2 to 5.6 and 5.10 related to the remote measurement of emission parameters such as frequency, field strength, spectrum occupancy, bandwidth and type of modulation. This task can also include listening (aural monitoring) to emissions and direction finding of their sources, identification and signal analysis, as described in §§ 5.7 and 5.8. All these functions are carried out independently by each monitoring station.

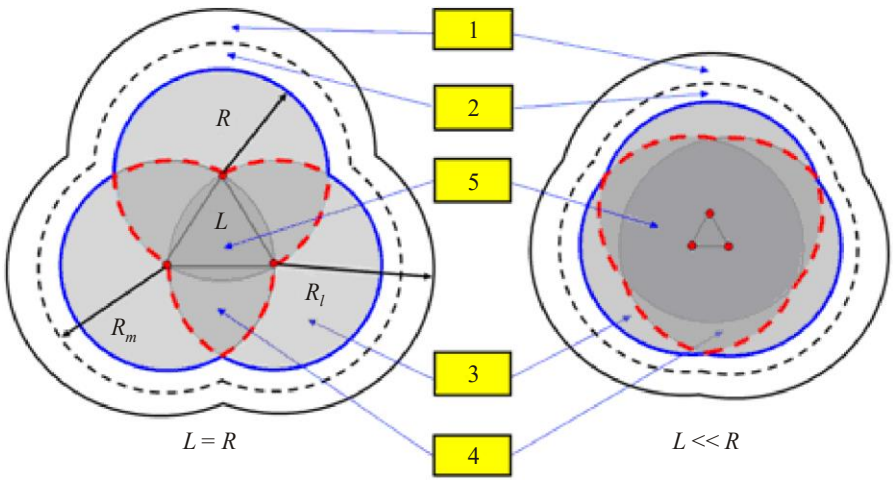
The second task involves the location of emission sources through use of the SSL mode in the HF band (see § 5.7.3.4) or the triangulation mode in all frequency ranges through processing of bearing data obtained from two or more direction finders or from TDOA processing obtained from three or more monitoring stations. The specific features of triangulation-based location are described in § 5.7.3.1.

Given that the measuring receiver sensitivity will be different for different monitoring functions, several coverage zones exist, as are conventionally shown in Fig. 7-42, which portrays three monitoring stations with different distances $\boldsymbol{L}$ between them. Bearing in mind that the receiver sensitivity is usually at maximum for listening, somewhat lower for measuring signal characteristics, and at minimum for direction finding, it is possible – as can be seen from Fig. 7-42 – to identify three coverage zones (1 – 3) with radiuses $\boldsymbol{R_l}$, $\boldsymbol{R_m}$ and $\boldsymbol{R}$ (in the interests of simplicity, the zones are at this stage considered to be circular).

Where direction finding is concerned, zone 3 constitutes the land area within which sufficiently reliable bearings are obtained.

FIGURE 7-42

Monitoring coverage zones for AOA stations



Spectrum-6.8-01

These three coverage zones are unique to each station and do not depend on one another. Therefore, the overall listening, emission parameter measurement and direction-finding blanket zones increase as the distances between the stations increase, up to $\boldsymbol{L} = \sqrt{3}\ \boldsymbol{R}$. Where $\boldsymbol{L} > \sqrt{3}\ \boldsymbol{R}$, non-covered areas will appear between the direction-finding coverage zones of the different stations.

The behaviour is different in the case of location coverage zones, which correspond to the overlapping direction-finding coverage zones from two or three stations (zones 4 and 5, respectively, in Fig. 7-42). These zones, and especially zone 5, become smaller as the distance $\boldsymbol{L}$ between the stations increases, this being particularly rapid in the range $\boldsymbol{R} < \boldsymbol{L} < \sqrt{3}\ \boldsymbol{R}$, when zones 4 and 5 become considerably smaller than the overall direction-finding zone. Where $\boldsymbol{L} \geq \sqrt{3}\ \boldsymbol{R}$, direction-finding coverage zone 5 (three stations) disappears, and with $\boldsymbol{L} > 2\ \boldsymbol{R}$ direction-finding coverage zones 4 (two stations) disappear, there being then no point at which emitter location measurements are possible.

At the same time, where there is a decrease in $\boldsymbol{L}$ and an increase in the overall location coverage zone, the location uncertainties at the periphery of this coverage zone increase considerably because the bearings from all three stations in these areas intersect one another at increasingly acute angles as the boundary of the zone is approached. This increases the difficulty of finding transmitters by means of homing by mobile stations at the periphery of the overall location coverage zone where $\boldsymbol{L} << \boldsymbol{R}$.

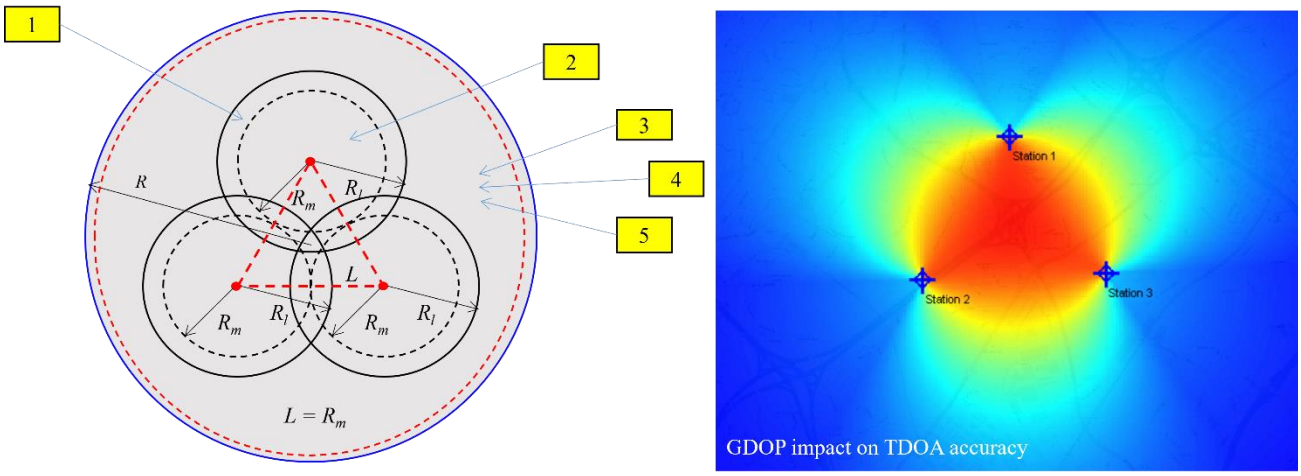
It should be noted the principles above describing siting and limitations of AOA stations do not always apply to networks of stations equipped with TDOA capabilities. While limitations exist related to coverage, the area over which location measurements can be made is larger than the individual coverage area of the individual stations as indicated in left side of Fig. 7-43. This is due to the use of advanced correlation techniques associated with TDOA. Zones 1 and 2 illustrate listening and monitoring ranges (similar to the AOA example). However, zones 3, 4 and 5 show where TDOA correlation can result in either a hyperbolic line of bearing, a line of bearing or a location result. Because of correlation gain achieved by TDOA processing, positive SNR is not needed at all stations for successful location measurements, and this leads to a very different approach to laying out a network of TDOA stations for blanket coverage.

The right side of the figure shows the limitation of TDOA stations resulting from GDOP and the impact on accuracy. In the simple three station example, the best accuracy is indicated in red and falls inside the boundary formed by the stations. Outside of the boundary, TDOA can still produce results, but with less accuracy and

may resemble lines of bearing. More information can be found on procedures for siting TDOA, Hybrid AOA/TDOA, and AOA stations in Report ITU-R SM.2356. A comprehensive comparison of TDOA and AOA techniques can be found in Report ITU-R SM.2211.

FIGURE 7-43

Monitoring coverage zones for TDOA stations



Nevertheless, Figs 7-42 and 7-43 graphically show that careful network planning is critical especially if the aim is to achieve blanket coverage of a given land area with the ability to locate emitters.

Achieving blanket location coverage of a sufficiently large territory using fixed monitoring stations in the VHF/UHF frequency bands requires a large number of stations sited at relatively short separation distances, and results in an increase in costs. To reduce the number of fixed stations, greater separation distances may be used, resulting in some areas being excluded from the location coverage zone. These areas can be covered using mobile stations working interactively with the fixed stations. In such cases, it is advisable to ensure that the network provides blanket direction-finding or TDOA coverage by means of the fixed monitoring stations so that they can then interact with the mobile stations to support location measurements throughout the territory. This will significantly boost the operating efficiency of the mobile stations, including their homing operations, for finding particular transmitters.

With increased separation distances between fixed monitoring stations operating in the VHF/UHF frequency bands, an increased burden is placed on mobile monitoring stations. Therefore, an integral part of planning includes establishing the optimum ratio between the number of fixed and mobile stations and depends on the configuration of fixed monitoring stations in the network.

The planning methodology for spectrum monitoring networks differs considerably between the VHF/UHF and the HF bands. The size and shape of monitoring coverage zones in the VHF/UHF bands are influenced to a great extent by terrain making it necessary to use the corresponding radio wave propagation models in all calculations and simulations. If blanket coverage is to be achieved, stations should be sited no further than 30-60 km apart. However, this is dependent on many factors that are described further in § 2.5 of Chapter 2 and in the reference documents. In the HF bands, terrain does not have an appreciable influence on the shape of monitoring coverage zones. For omnidirectional antennas, the skywave (reflected from the ionosphere) coverage zones will be circular with radiuses in the order of 2 000-2 500 km. One of the features of ionospheric radio wave propagation is the presence of “blind spots” (“silent zones”), which need to be considered in the planning and optimization of HF monitoring networks, as it is described in [Krutova *et al*., 2008].

Planning and optimization of monitoring networks in the VHF/UHF bands is described in detail in Report ITU-R SM.2356, covering AOA, TDOA and hybrid architectures. Minimum requirements for developing countries are discussed in Recommendation ITU-R SM.1392.

References

Related ITU-R Recommendations and Reports

Recommendation ITU-R SM.1392 – *Essential requirements for a spectrum monitoring system for developing countries*

Report ITU-R SM.2211 – *Comparison of Time-Difference-of-Arrival and Angle-of-Arrival Methods of signal geolocation*

Report ITU-R SM.2356 – *Procedures for planning and optimization of spectrum-monitoring networks in the VHF/UHF frequency range*

NOTE – In every case the latest edition of the ITU-R Recommendation and Report should be used.

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7.9 Measurement uncertainty

7.9.1 Introduction

The terms “uncertainty”, “error” and “accuracy” are often used but not always in a correct way. For every measurement made, a value is obtained that may differ from the true value. If the true value could be known then the error could be expressed as the difference between the measured value and the true value. Depending on the process and equipment used for the measurement, raw results are only an estimate of the real value to measure.

Since the true value is unknown, the uncertainty can only be associated with a measured value. The absolute uncertainty is a quantity expressed in the same unit as the measured value itself and describes an interval into which the true value falls with a given probability.

The relative uncertainty is the quotient of the absolute uncertainty and the best possible estimate of the true value.

The lower is the uncertainty the higher is the accuracy, that is, however, difficult to quantify.

7.9.2 Overview and definition of measurement uncertainty

Applying a procedure measurement, with equipment set, in a controlled environment does not produce the same result for each sample measurement.

This characterises the variability of the measurement. This variability may be due to the uncertainty of the equipment test, to the operator, to the measurement environment or to other aspects. To evaluate the real result, it is necessary to specify this variability.

Basically, the result may be characterized by an average value and a standard deviation interval. This characterizes the uncertainty. Two different approaches to express uncertainty are commonly used. These two types are designed as Type A and Type B. They do not refer to the nature of the uncertainty contributor but as a method of estimating which lead to the assessment of the uncertainty.

A Type A uncertainty estimate is an estimate derived from the statistical analysis of experimental data. This estimate should not be identified as "random" components of uncertainty. The average of n samples is usually taken into account, and the variability of the result is characterised by the standard deviation. Common probability distributions are detailed in § 7.9.3. The Type A is dedicated to the evaluation of the standard uncertainty.

A Type B uncertainty estimate is used when the uncertainty cannot be evaluated statistically. The estimate is based on past experience, on data available in Handbooks or extracted from calibration reports. The Type B is used to assess the standard uncertainty, the combined standard uncertainty and the expanded uncertainty.

In practice, the Type A is used as a reckoning of raw results and the Type B is based on the analysis of results and influence factors in the measurement.

The combined standard uncertainty is the standard uncertainty of the result of a measurement when that result is obtained from the values of a number of other quantities, equal to the positive square root of a sum of terms, the terms being the variances or covariances of these other quantities weighted according to how the measurement result varies with changes in these quantities.

The expanded uncertainty is quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand.

Practical aspect of these definitions is detailed in § 7.9.4.

To summarize, the uncertainty of a measurement is expressed according to two parameters which are defined as:

– an average value,

– a standard deviation.

In addition, a confidence level might be provided (for example, the value and the interval are true with a probability of 95%).

Taking into account all parameters of each element of the measurement process and reckoning uncertainties lead to provide a value and an interval which include the real value with a certain confidence level. The aim is to carry out measurement comparable and reproducible. The reproducibility of a measurement is essential to improve the confidence in a measurement.

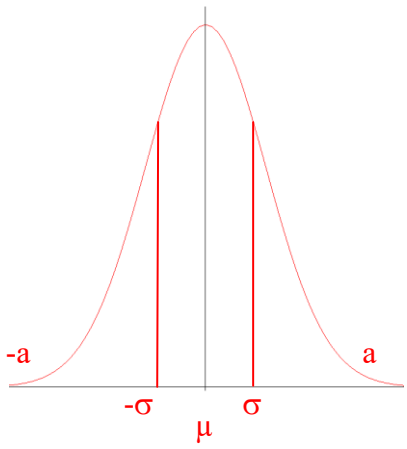
A full consideration of all identifiable source of uncertainty contributes to valid results compare to a theoretical study. The uncertainty explains and justifies observed differences in results. Nevertheless, a special care should be taken during measurement, a systematic bias could occur. One way to avoid such situation is to carry out inter-comparison measurement with other measurement team and/or other measurement chain in order to compare, to improve, to adjust and/or to correct procedure and measurement setup.

7.9.3 Common distribution functions to express uncertainty

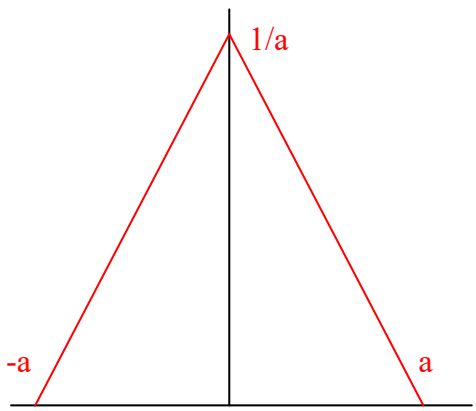
The variability of a set of values may be described with probability distributions. The most common mathematical functions used to express measurement uncertainty are summarized in Table 7-10.

TABLE 7-10

Summary of probability distributions

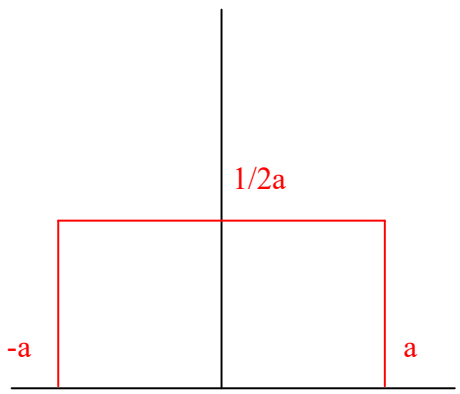
Normal distribution		
	Mathematical function $f(x;\mu,\sigma) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\left[\frac{(x-\mu)^2}{2\sigma^2}\right]}$ μ is the average value σ is the standard deviation	Standard deviation For a confidence interval of 68% $\sigma = a$ For a confidence interval of 95% $\sigma = \frac{a}{2}$ For a confidence interval of 99.7% $\sigma = \frac{a}{3}$

In a set of readings, this Normal or Gaussian distribution is the most used for repeated observations which varies around an average value.

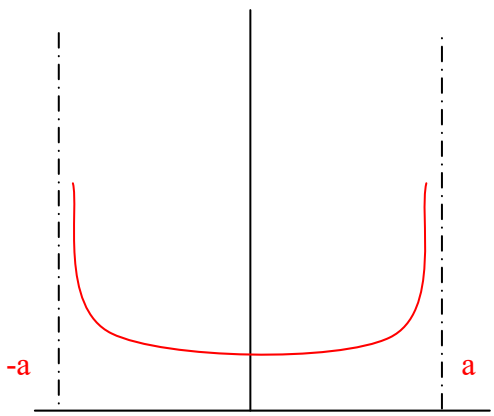
Triangular distribution		
	Mathematical function $f(x) = \begin{cases} \frac{(x+a)}{a^2} & \text{for } -a \le x \le 0 \\ \frac{(a-x)}{a^2} & \text{for } 0 \le x \le a \end{cases}$	Standard deviation $\sigma = \frac{a}{\sqrt{6}}$

The minimum and the maximum values of this distribution are known.

TABLE 7-10 (*end*)

Rectangular or uniform distribution		
	Mathematical function $f(x) = \frac{1}{2a}$	Standard deviation $\sigma = \frac{a}{\sqrt{3}}$

The particularity of this function is that the probability of obtaining any values between [–a; a] is 1. All values are equally probable.

U-shape distribution		
	Mathematical function $f(x) = \frac{1}{\pi\sqrt{a^2 - x^2}}$ for $-a < x < a$	Standard deviation $\sigma = \frac{a}{\sqrt{2}}$

7.9.4 Application

The measurement uncertainty for a monitoring station should be evaluated for those measurements addressed in the following sub-clauses, taking into consideration each of the quantities listed there. The standard uncertainty $u(x_i)$ in decibels and the sensitivity coefficient c_i shall be evaluated for the estimate x_i of each quantity.

The combined standard uncertainty $u_c(y)$ of the estimate y of the measured is calculated as a weighted root sum square (r.s.s.):

$$u_c(y) = \sqrt{\sum_i c_i^2 u^2(x_i)} \tag{7-36}$$

The expanded measurement uncertainty for a monitoring station U_{ms} is calculated as:

$$U_{ms} = 2u_c(y) \tag{7-37}$$

and should be stated in the measurement report.

NOTE 1 – The coverage factor $k = 2$ yields approximately a 95% level of confidence for the near-normal distribution typical of most measurement results.

This coverage factor is used to express the level of confidence as assumed in § 7.9.3 on the description of normal distribution.

Principally compliance or non-compliance with a regulatory limit can e.g. be determined in the following manner using one of the following two approaches:

– *1st approach:*

measurement uncertainty U_{ms} as small as possible (V_{meas} is the measured value):

For the operator of a radio service: Compliance with a limit occurs if $V_{meas} + U_{ms}$ complies with the limit.

For the regulator: Non-compliance with a limit can be demonstrated if $V_{meas} - U_{ms}$ does not comply with the limit.

– *2nd approach:*

measurement uncertainty U_{ms} should not exceed a recommended maximum uncertainty U_{rec}:

If U_{ms} is less than or equal to U_{rec} then:

– compliance occurs if no measured value exceeds the limit.

– non-compliance occurs if any measured value exceeds the limit.

For the operator: if U_{ms} is greater than U_{rec} then:

– compliance occurs if no measured value, increased by ($U_{ms} - U_{rec}$), exceeds the limit.

– non-compliance occurs if any measured value, increased by ($U_{ms} - U_{rec}$), exceeds the limit.

For the regulator: if U_{ms} is greater than U_{rec} then:

– compliance occurs if no measured value, decreased by ($U_{ms} - U_{rec}$), exceeds the limit.

– non-compliance occurs if any measured value, decreased by ($U_{ms} - U_{rec}$), exceeds the limit.

7.9.5 Example of an uncertainty calculation

Measurement of field strength (E) in a fixed or mobile monitoring station in the frequency range 30 to 3 000 MHz is one of their tasks.

The measured E is calculated as:

$$E = V_r + L_c + AF + +\delta V_{sw} + \delta V_{sel} + \delta V_{nf} + \delta M + \delta AF_f + \delta AF_h + \delta A_{dir} + \delta A_{cp} + \delta A_{bal} + \delta SR \qquad (7\text{-}38)$$

The uncertainty of E is calculated from the uncertainties of the terms on the right-hand side by adding their squares and then calculating the square root of the sum (see Table 7-11).

TABLE 7-11

Values of input quantities for about 30 MHz to 3 000 MHz
(to be calculated for each individual antenna, polarization and subrange)

Input quantity	**Refer to note**	X_i	**Uncertainty of x_i**		$u(x_i)$ **(dB)**	c_i	$(c_i\, u(x_i))^2$ **(dB)**
			(dB)	**Pr Dist; k**			
Receiver reading	(1)	V_r	±0.1	$k = 1$	0.10	1	0.01
Attenuation: antenna-receiver	(2)	L_c	±0.1	$k = 2$	0.05	1	0.0025
Antenna factor	(3)	AF	±2.0	$k = 2$	1.00	1	1.00
Receiver corrections:							
– Sine wave voltage	(4)	δV_{sw}	±1.0	$k = 2$	0.5	1	0.25
– Receiver selectivity	(5)	δV_{sel}	–0.5	Rectangular	0.28	1	0.0784
– Noise floor proximity	(6)	δV_{nf}	±0.5	$k = 2$	0.25	1	0.0625
Mismatch: antenna-receiver	(7)	δM	+0.9/–1.0	U-shaped	0.67	1	0.4489

TABLE 7-11 (*end*)

Input quantity	Refer to note	X_i	Uncertainty of x_i		$u(x_i)$ (dB)	c_i	$(c_i\, u(x_i))^2$ (dB)
			(dB)	Pr Dist; k			
Antenna factor corrections:							
– AF frequency interpolation	(8)	δAF_f	±0.3	Rectangular	0.17	1	0.0289
– AF height deviations	(9)	δAF_h	±0.5	Rectangular	0.29	1	0.0841
– Directivity difference	(10)	δA_{dir}	±0.5	Rectangular	0.29	1	0.0841
– Cross-polarization	(11)	δA_{cp}	±0.9	Rectangular	0.52	1	0.2704
– Balance	(12)	δA_{bal}	±0.3	Rectangular	0.17	1	0.0289
Partial sum							2.3487
Shadowing and reflections:							
Shadowing	(13)	δSR_1	±1.0	Rectangular	0.56	1	0.3136
Reflections	(14)	δSR_2	±4.0	Triangular	1.63	1	2.6569
Total sum							5.3192
Combined uncertainty $u_c(y) = \sqrt{\sum_i c_i^2 u^2(x_i)}$							2.3063
Expanded combined uncertainty (k = 2)							4.6126

Comments on the estimates of input quantities (first column of Table 7-11)

The uncertainty associated with an estimate x_i of an input quantity in Table 7-11 is the largest uncertainty considered likely within the frequency range covered by this table, provided that it is consistent with accuracy of the measurement specified in Recommendation ITU-R SM.378. Superscripts to input quantities refer to the numbered comments below. The expanded uncertainties are to be compared to the values of U_{rec}.

The assumptions which led to the values in Table 7-11 may not be appropriate for a particular monitoring station. When a monitoring station evaluates its expanded measurement uncertainty U_{ms} then it has to consider the information available on its particular measuring system, including equipment characteristics, the quality and currency of calibration data, the known or likely probability distributions, and measurement procedures.

A monitoring station may find it advantageous to evaluate its uncertainties over subdivisions of the frequency range, particularly if a dominant input quantity varies significantly over that range.

Notes from the second column of Table 7-11:

The following Notes are intended to provide some guidance to monitoring stations confronted with data or situations different to those assumed here.

1) Receiver readings will vary for reasons, which include measuring system instability, receiver noise, and meter scale interpolation errors. The estimate of V_r is the mean of many readings, with a standard uncertainty given by the experimental standard deviation of the mean.

2) An estimate of the attenuation uncertainty L_c of the connection between the receiver and the antenna, was assumed to be available from a calibration report, along with an expanded uncertainty and a coverage factor.

3) An estimate of the free space antenna factor AF was assumed to be available from a calibration report, along with an expanded uncertainty and a coverage factor.

4) An estimate of the correction δV_{sw} for receiver sine-wave voltage accuracy was assumed to be available from a calibration report, along with an expanded uncertainty and a coverage factor.

   Comment: If a calibration report states only that the receiver sine-wave voltage accuracy is within a given tolerance (±2 dB), then the estimate of the correction δV_{sw} should be taken as zero with a rectangular probability distribution having a half-width of 2 dB.

5) δV_{sel} takes into account the uncertainty due to limited resolution bandwidth of the measuring receiver or spectrum analyzer including the uncertainty of any correction factor to compensate for the effect

of limited resolution bandwidth. E.g. an RMS detector is used for the measurement of a CDMA signal with a measurement bandwidth of 10% of the occupied bandwidth. In this case the correction factor will be 10 dB and the uncertainty of this correction factor is in the order of 0.5 dB in case of a ±10% bandwidth tolerance.

6) Depending on the distance of the transmit antenna the noise floor of a measuring receiver may or may not be sufficiently far below the input voltage that its effect is negligible on measurement results.

7) In general, the antenna will be connected to port 1 of a two-port network whose port 2 is terminated by a receiver of reflection coefficient Γ_r. The two-port network, which might be a cable, attenuator, attenuator and cable in tandem, or some other combination of components, can be represented by its S-parameters. The mismatch correction is then:

$$\delta M = 20\log_{10}[(1-\Gamma_e S_{11})1-\Gamma_r S_{22}) - S_{21}^2\Gamma_e\Gamma_r] \quad (7\text{-}39)$$

where Γ_e is the reflection coefficient seen looking into the output port of the antenna when it is set up for field-strength measurement. All parameters are with respect to 50 Ω.

When only the magnitudes, or extremes of magnitudes, of the parameters are known, it is not possible to calculate δM, but its extreme values $\delta M^{\pm}$ are not greater than:

$$\delta M^{\pm} = 20\log_{10}[(1 \pm (|\Gamma_e||S_{11}| + |\Gamma_r||S_{22}| + |\Gamma_e||\Gamma_r||S_{11}||S_{22}| + |\Gamma_e||\Gamma_r||S_{21}|^2)] \quad (7\text{-}40)$$

The probability distribution of δM is approximately U-shaped, with width not greater than $(\delta M^+ - \delta M^-)$ and a standard deviation not greater than the half-width divided by √2.

For field-strength measurements, an antenna specification of VSWR ≤ 2.0:1 was assumed, implying $|\Gamma_e| \leq 0.33$. It was also assumed that the connection to the receiver was a well-matched cable ($|S_{11}| << 1$, $|S_{22}| << 1$) of negligible attenuation ($|S_{21}| \approx 1$), and that the receiver RF attenuation was 0 dB, for which the VSWR ≤ 2.0:1 implies $|\Gamma_r| \leq 0.33$.

The estimate of the correction δM was zero with a U-shaped probability distribution having width equal to the difference $(\delta M^+ - \delta M^-)$.

Comment: The expressions for δM and $\delta M^{\pm}$ show that increasing the attenuation of the well-matched two-port network preceding the receiver can reduce mismatch error. The penalty is a reduction in measurement sensitivity.

For some antennas at some frequencies, the VSWR may be much greater than 2.0:1.

Precautions may be needed to ensure that the impedance seen by the receiver complies with the specification of VSWR ≤ 2.0:1 when a complex antenna is used.

8) When an antenna factor is calculated by interpolation between frequencies at which calibration data are available, the uncertainty associated with that antenna factor depends on the frequency interval between calibration points and the variability of antenna factor with frequency. Plotting calibrated antenna factor against frequency helps visualise the situation.

The estimate of the correction δAF_f for antenna factor interpolation error was zero with a rectangular probability distribution having a half-width of 0.3 dB.

Comment: At any frequency for which a calibrated antenna factor is available, the correction δAF_f does not need to be considered.

9) The height dependence of antenna factor for a complex antenna will differ from that for a dipole antenna, which has been considered for the given amount of uncertainty. The estimate of the correction δAF_h was zero with a rectangular probability distribution having a half-width evaluated from the behaviour of biconical and log-periodic antenna factor with height.

10) The responses of a complex antenna in any direction should be considered relative to the direction of the main lobe for which the antenna factor has been measured.

The correction δA_{dir} was zero with a rectangular probability distribution having the appropriate width.

Comment: A non-zero estimate of δAdir with reduced uncertainty could be evaluated from the known pattern of the measuring antenna, and applied as a function of frequency and angle of incidence.

11) The cross-polarization response of a dipole antenna can usually be considered to be negligible. The estimate of the correction δA_{cp} for cross-polarization response of a log-periodic antenna was zero with a rectangular probability distribution having a half-width of 0.9 dB, corresponding to the CISPR16-1 cross-polarization response tolerance of −20 dB.

Comment: If a dipole is used as the measuring antenna the correction δA_{cp} is negligible.

12) The effect of an unbalanced antenna is greatest when the input coaxial cable is aligned parallel to the antenna elements. The estimate of the correction δA_{bal} for antenna unbalance was zero with a rectangular probability distribution having a half-width evaluated from the performance of commercially available antennas.

13) Effects of shadowing may be considerable in cases of fixed monitoring stations.

The estimate of the correction δSR_1 was zero with a rectangular probability distribution having a half-width of 1 dB as an example. It is difficult to estimate the shadowing effect of e.g. a building.

14) Effects of reflections may be reduced by field-strength averaging with antenna height variations and variation of the vehicle position in cases of mobile monitoring stations.

7.9.6 References

European Cooperation for Accreditation of Laboratories [April, 1997] Expression of the Uncertainty of Measurement in Calibration, EAL-R2; and Supplement 1 to EAL-R2, EAL-R2-S1, November, 1997.

ISO/IEC Guide 99:2007(en) *International vocabulary of metrology — Basic and general concepts and associated terms (VIM)*

ISO/IEC Guide 98-1:2024(en) *Guide to the expression of uncertainty in measurement*

TAYLOR, B. N. and KUYATT, C. E. [September, 1994] *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*. United States Department of Commerce Technology Administration, National Institute of Standards and Technology, NIST Technical Note 1297.

7.10 Antenna processing and spatial diversity

7.10.1 Introduction

Although antenna processing and spatial diversity have been used for the past 30 to 40 years, the technology has primarily been used in communication systems and devices. RF enhancements and reduced size and cost of signal processing have largely developed these techniques in the last few years, increasing the amount of data that can be transmitted, and minimizing the effects of fading and interference on the same frequency.

Spectrum monitoring can also benefit from the use of such techniques to adapt monitoring systems to new technologies and new transmission schemes. Development of wide band wireless cellular systems and flexible spectrum applications have led to a more complex and congested radio environment.

Antenna processing can improve the performance of technical monitoring functions such as interference detection, diagnosis, and signal isolation. Characterization and identification of transmitters, detection and identification of interferers, multipath determination, direction finding, emitter location (AOA, TOA/TDOA determination), and other factors can be optimized.

In difficult and complex monitoring environments (as described below), spectrum monitoring can benefit from the application of such techniques:

1) urban areas and mountainous locations with shadowing by large obstacles, flat and selective fading, multipath reflections, etc.;

2) areas with high re-use of frequencies for:
   - single-frequency network (SFN) digital TV;
   - cellular networks;

3) implementation of dynamic spectrum allocation and convergence where the simultaneous use of several radio-communication networks leads to radio transmitters sharing the same frequency bands.

In this context, antenna processing is of particular benefit, given its ability to isolate the transmitters and the associated propagation paths.

7.10.2 Antenna processing for spectrum monitoring

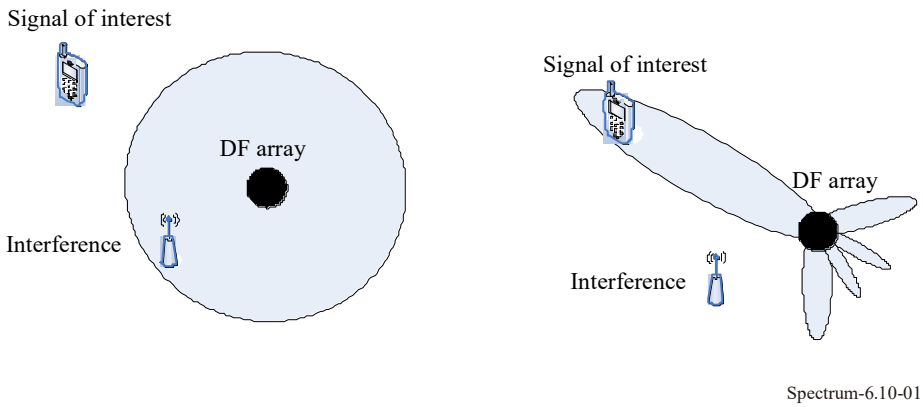
The main applications of antenna processing are interference cancellation, transmitter separation, sensitivity optimization, and multipath effects cancellation (mainly the case of frequency fading).

Interference cancellation: Antenna filtering favours one transmitter direction and rejects the interference signal. Then the transmitter of interest can be demodulated and measured under optimal conditions.

Transmitter separation: Antenna filtering can separate several signals at the same frequency. Then the transmitters can be demodulated and identified.

FIGURE 7-44

Example of antenna processing: the sensitivity is improved by creation of a beam and the interference is cancelled

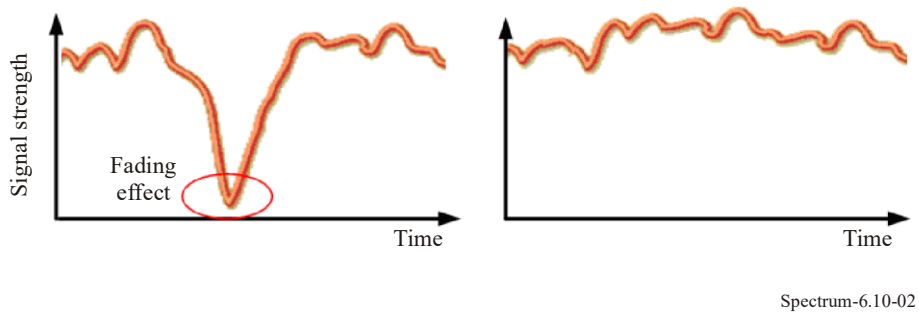


Sensitivity optimization: Antenna filtering forms a beam towards the desired signal, thus improving sensitivity.

Fading cancellation: Multipath causes random signal fading as reflections destructively (or constructively) superimpose on one another, effectively cancelling part of the signal energy for brief periods of time. The goal of antenna filtering is to lower these effects by using the spatial diversity offered by multiple antenna processing.

FIGURE 7-45

Example of a signal without antenna processing: A deep fading prevents demodulation. In the right figure, the fading effect is reduced by antenna processing and spatial diversity



All these functionalities are beneficial to improve monitoring tasks, such as interference analysis or transmitter identification in a complex environment.

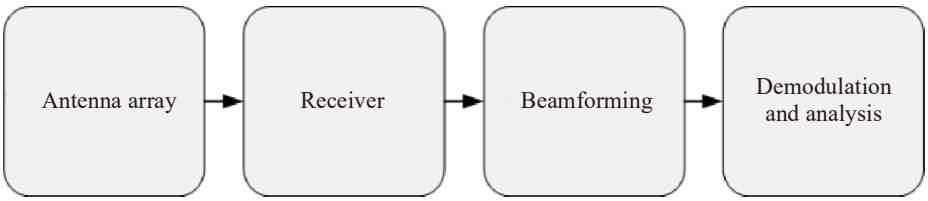
Antenna processing and spatial diversity use multi antenna arrays connected to coherent receivers making it easy to implement a multi-channel correlative interferometer or an advanced resolution direction finder with software updates.

7.10.3 Antenna processing principles

Antenna processing adapts the receiver to the local radiofrequency environment by the use of real time modification of the antenna beam pattern with a main lobe focusing towards the transmitter of interest.

FIGURE 7-46

Schemes of an antenna processing system



Spectrum-6.10-03

A typical antenna processing systems is composed of:

– multiple antenna elements (one antenna array);

– multiple receivers with phase coherent processing;

– signal processing algorithms that vary the ways in which those elements are used as a function of operational scenario;

– output processing for each of the selected incoming signals, like demodulation, spectral analysis, or identification.

7.10.3.1 Antenna arrays and receiver

Multi antenna arrays have advantages compared with the use of a single antenna. First is the exploitation of spatial diversity which provides enhanced system reliability by minimizing fading of the signals. Second is beamforming, which focuses energy and thereby provides a better signal to the user.

7.10.3.2 Beamforming

Two types of antenna processing techniques can be defined, conventional beamforming and adaptive beamforming. Conventional beamforming implements several fixed beam patterns. A decision is made to select the appropriate beam. Adaptive beamforming allows the antenna to steer the beam to any direction of interest while simultaneously eliminating interfering signals.

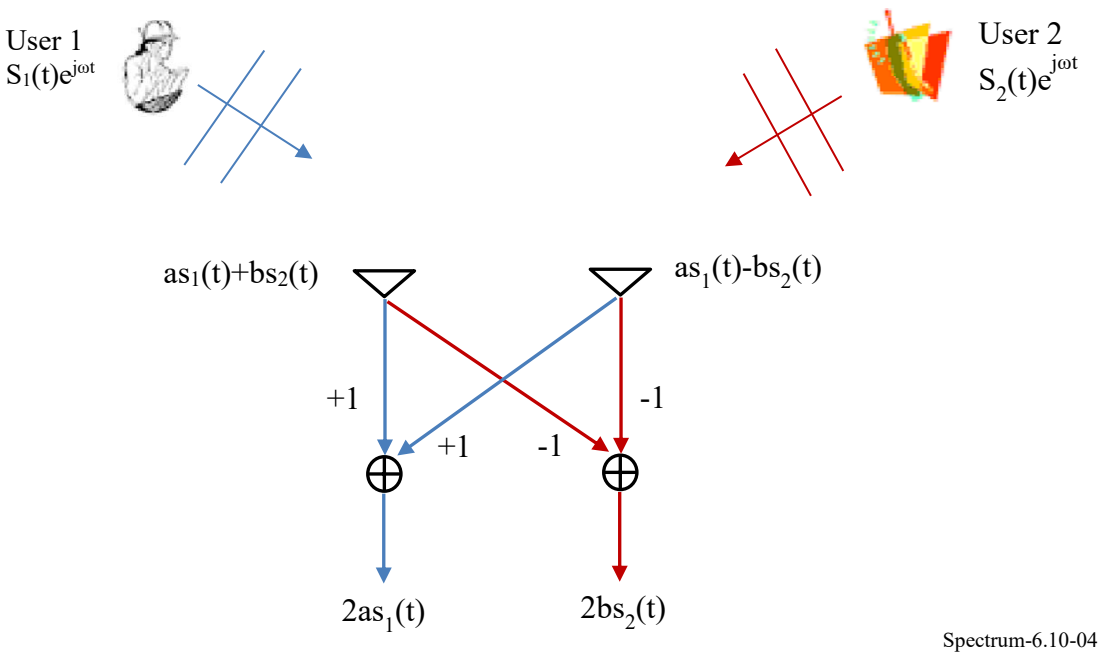
7.10.3.2.1 Antenna filtering or conventional beamforming

A beamformer array generates a single-channel signal from multiple antennas signals by filtering the individual signals (adaptive filters) and adding them together, i.e. combining the signals linearly with frequency-dependent weights in amplitude and phase. For a given weighting function, the spatial response of such a beamformer can be described by an antenna pattern showing the dependence of array gain on direction.

Figure 7-47 shows a simple scenario for conventional beamforming: from an antenna array receiving both “User1” and “User2” signals; the algorithm provides two outputs representing each signal by applying different weights to the incoming signals.

FIGURE 7-47

Example of a simple scenario with a 2-antenna array



7.10.3.2.2 Adaptive antenna or adaptive beamforming

Adaptive beamforming can respond to the impact of interference (or other signals present at the level of the antenna array) by changing the directionality of the array. The phase and amplitude of the signals from different antennas is combined in such a way that the direction and pattern of the antenna beam is optimized for the desired signal.

Adaptive array methods can be classified according to the criteria used for selecting weights to combat a given interference structure and the algorithms used for changing the weights in time. Among the more useful weight-selection criteria are noise-cancellation, eigenvector decomposition and constrained beamforming which is closely related to the known direction minimum-variance and maximum-likelihood criteria. Noise cancellation uses an interference-only signal to remove correlated interference from a target-plus-interference signal. Eigenvector decomposition can be used to estimate the directions of signal arrivals and cancel all but one of the signals.

A wide application of adaptive beamforming was introduced with the 5G mobile radio system specified by 3GPP. In this case, the antenna consists of an array of many dipoles, each one being equipped with its own transmitting unit. By driving these dipoles with a specific phase and amplitude, the antenna can create multiple beams into different directions and with different gain simultaneously. This is commonly called an active antenna system (AAS).

7.10.3.3 Demodulation and analysis

When the adaptive antenna algorithms have been applied to the input signal of the array, the signal may often be demodulated and analysed in order to identify the transmitter. This is because the SNR or SINR is improved and the overall gain is higher since the power on each receiving antenna is coherently combined. Diversity gain results when independent channels exist between the transmitter and receiver such that the likelihood of all channels experiencing a deep fade simultaneously is greatly reduced.

7.11 Required documentation

For effective work of the monitoring station, a collection of relevant documentation and software should be available at a station. Documentation is also needed for better understanding and application of this Handbook

on Spectrum Monitoring. Documents can be stored in digital format, to save place and to ease their exploration. The following §s comprise a set of such kind of documents and software.

7.11.1 Basic and general international documents

The basic document covering the use of the radio-frequency spectrum is the ITU Radio-Regulations (RR).

The RR, as a principal instrument of the international radio-regulatory arrangement, are based on the use of two main concepts:

– frequency allocations to mutually compatible radiocommunication services operating in specific parts of the spectrum;

– voluntary or obligatory regulatory procedures (for coordination, notification and recording) that are adapted to the allocation structure.

The RR are developed, revised and adopted by World Radiocommunication Conferences (WRC) and published by ITU. According to RR Article **20** (Service publications and online information systems) (WRC-07) the following publications are issued by ITU and may be included in the monitoring stations documentation:

List I – *The International Frequency List.*

List IV – *List of Coast and Special Service Stations.*

List V – *List of Ship Stations and Maritime Mobile Service Identity Assignments.*

List VIII – *List of International Monitoring Stations.*

List VIII A – *List of Stations in the Space Radiocommunication Services and in the Radio Astronomy Service.*

Manual for Use by the Maritime Mobile and Maritime Mobile-Satellite Services

However, the RR are oriented mainly toward those matters that have a global or regional character, and in many areas, there is a place for making special arrangements on a national, bilateral or multilateral basis.

7.11.2 Minimum documentation that should be available at monitoring stations

Table 7-12 contains the minimum documentation, which should be available at monitoring stations. It has to be adopted to the individual tasks of the monitoring station and to the structure of whole monitoring system.

TABLE 7-12

Minimum documentation which should be available at monitoring stations

International	National
ITU BR International Frequency Information Circular (IFIC)(1) Regional frequency plans Radio Regulations(1) Bilateral and regional agreements ITU List VIII (List of International Monitoring Stations)(1) ITU List IV (Coast Stations and Special Service Stations)(1) ITU List V (Ship Stations *and Maritime Mobile Service Identity Assignments*)(1), (3) ITU-R Recommendations(4) Handbook on Spectrum Monitoring(1) Handbook on National Spectrum Management	National frequency allocation table National frequency assignments (data base) National laws and ordinance acts Maps (or digital maps) of different scales(2) Road maps and city maps(2) User manuals and service manuals for all equipment Telephone dictionary of the own organization and other important numbers Public telephone dictionary, or other access Work instructions Case documentation(5)

Notes to Table 7-12:

(1) These documents should be available at least at HF monitoring stations.

(2) Maps are required at the station and in each vehicle.

(3) Information contained in this List can also be obtained via the Internet-based ITU-MARS (Maritime Mobile Access and Retrieval System) (https://www.itu.int/en/ITU-R/terrestrial/mars/Pages/default.aspx).

(4) ITU-R Recommendations are to be used as a reference. Nevertheless, the essentials can be transformed into measurement instructions.

(5) As already indicated in § 2.3.3 of Chapter 2, the documentation of past cases can be taken as a reference.

7.11.3 ITU-R Recommendations

ITU-R Recommendations constitute a set of recommended technical and operating standards for radiocommunications. They are the result of studies undertaken by Radiocommunication Study Groups.

The ITU-R Recommendations are approved by ITU Member States. Except for those incorporated by reference in the Radio Regulations (Vol.4), their implementation is not mandatory; however, as they are developed by experts from administrations, operators, the suppliers and other organizations dealing with radiocommunication matters from all over the world, they enjoy a high reputation and are implemented Worldwide.

ITU-R Recommendations are divided into Series according to the subjects they cover, as follows:

BO	Satellite delivery
BR	Recording for production, archival and play-out; film for television
BS	Broadcasting service (sound)
BT	Broadcasting service (television)
FS	Fixed service
M	Mobile, radiodetermination, amateur and related satellite services
P	Radio-wave propagation
RA	Radio astronomy
RS	Remote sensing systems
S	Fixed-satellite service
SA	Space applications and meteorology
SF	Frequency sharing and coordination between fixed-satellite and fixed service systems
SM	Spectrum management
SNG	Satellite news gathering
TF	Time signals and frequency standards emissions
V	Vocabulary and related subjects

The ITU-R Recommendations and Reports are published and available on the ITU webpages: https://www.itu.int/pub/R-REC and https://www.itu.int/pub/R-REP.

7.11.4 Radiocommunication SG 1 Recommendations and Reports

Those are the developed ITU-R Recommendations and Reports related to Spectrum Management. They contain essential information to monitoring stations.

See https://www.itu.int/rec/R-REC-SM/en for the Recommendations and https://www.itu.int/pub/R-REP-SM/en for the Reports.

NOTE – The latest versions of Recommendations and Reports should be used.

7.11.5 ITU-R Handbooks

As well as ITU-R Recommendations, ITU-R Handbooks are a set of technical and operational texts, based on ITU-R Recommendations and Reports, for radiocommunications with more practical features. They are also the result of studies undertaken by Radiocommunication Study Groups. They are revised and published every several years as and when the necessity arises. The relevant ITU-R Handbooks for monitoring tasks are as follows:

SG 01 Spectrum management

– Computer-aided Techniques for Spectrum Management (CAT) (https://www.itu.int/pub/R-HDB-01).

– National Spectrum Management (https://www.itu.int/pub/R-HDB-21).

– Handbook on Spectrum Monitoring (Superseded by the current version of the Handbook on Spectrum Monitoring).

SG 03 Radio-wave propagation

– Curves for Radio-wave Propagation over the Surface of the Earth (https://www.itu.int/pub/R-HDB-13).

– Ionosphere and its Effects on Radio-wave Propagation (https://www.itu.int/pub/R-HDB-32).

– Radiometeorology (https://www.itu.int/pub/R-HDB-26).

– Radio-wave Propagation Information for Predictions for Earth-to-Space Path Communications (https://www.itu.int/pub/R-HDB-32).

– Terrestrial land mobile radio-wave propagation in the VHF/UHF bands (https://www.itu.int/pub/R-HDB-44).

– Radio-wave propagation information for designing terrestrial point-to-point links (https://www.itu.int/pub/R-HDB-54).

SG 04 Satellite services

– Satellite Communications – Fixed Satellite Service (FSS) (https://www.itu.int/pub/R-HDB-42).

SG 05 Terrestrial Services

– Digital Radio-Relay Systems (https://www.itu.int/pub/R-HDB-24).

– Land Mobile (including Wireless Access) Volume 1: Fixed Wireless Access (https://www.itu.int/pub/R-HDB-25).

– Land Mobile (including Wireless Access) Volume 2: Principles and Approaches on Evolution to IMT-2000/FPLMTS (https://www.itu.int/pub/R-HDB-30).

– Land Mobile Handbook (including Wireless Access) – Volume 3: Dispatch and Advanced Messaging Systems (https://www.itu.int/pub/R-HDB-47).

– Land Mobile Handbook (including Wireless Access) – Volume 4: Intelligent Transport Systems (https://www.itu.int/pub/R-HDB-49).

– Handbook on International Mobile Telecommunications (IMT) (https://www.itu.int/pub/R-HDB-62).

SG 06 Broadcasting service

– DTTB Handbook – Digital terrestrial television broadcasting in the VHF/UHF bands (https://www.itu.int/pub/R-HDB-39).

– HF Broadcasting System Design (https://www.itu.int/pub/R-HDB-33).

SG 07 Science services

– Selection and Use of Precise Frequency and Time Systems (https://www.itu.int/pub/R-HDB-31).

– Satellite Time and frequency Transfer and Dissemination (https://www.itu.int/pub/R-HDB-55).

7.11.6 Relevant ITU-R software

Over the past few years, a growing number of administrations have requested engineering software to support their national and international frequency management activities. The programs are submitted by participants in the work the Radiocommunication Study Groups or by the Radiocommunication Bureau.

A detailed description of available computer programs, which might be of interest to radio spectrum management, is accessible electronically through the ITU Web site (https://www.itu.int/).

Examples of programs are:

1) ACP: Antenna Coverage Program.

2) IDWM: ITU Digitized World Map (IDWM) and Subroutine Library.

3) Calculation of Ground Waves (https://www.itu.int/en/ITU-R/study-groups/rsg3/Pages/iono-tropo-spheric.aspx).

4) *SMS4DC* a Spectrum Management System for Developing Countries.

5) MARS Maritime Mobile Access and Retrieval System the most up-to-date data registered in the ITU master Ship station database (https://www.itu.int/en/ITU-R/terrestrial/mars/Pages/default.aspx).

6) GLAD GLobal Administration Data System: an online data retrieval-system and a central repository of ITU-R common information concerning administrations and geographical areas (https://www.itu.int/en/ITU-R/terrestrial/fmd/Pages/glad.aspx).

Furthermore, databanks and computer programs on radio-wave propagation can be found at: https://www.itu.int/en/ITU-R/study-groups/rsg3/Pages/dtbank-dbsg3.aspx.

7.11.7 Internet websites

The World Wide Web (WWW) Internet addresses represent Web locations that have information relating to various aspects of spectrum monitoring and spectrum management.

The Web should be considered an important source of monitoring and management information, with useful software that may be downloaded, and to interact within national spectrum management organizations and with other monitoring organizations via electronic mail and other documentation.

Table 7-13 lists Internet World Wide Web sites that are relevant to readers which have interest in radio monitoring:

TABLE 7-13

Internet World Wide Web sites relevant to radio monitoring

Subject	Description/WWW address
ITU Global Directory	Administration's Contact Information: www.itu.int/GlobalDirectory/
ITU Radiocommunication Bureau	Homepage: https://www.itu.int/en/ITU-R/Pages/default.aspx
ITU Monitoring database	Monitoring database: https://www.itu.int/en/ITU-R/terrestrial/monitoring/Pages/default.aspx
ITU Spectrum management/monitoring	Study Group documents: https://www.itu.int/en/ITU-R/study-groups/rsg1/Pages/default.aspx
ITU-R Recommendation	www.itu.int/pub/R-REC
ITU-R Handbooks	www.itu.int/pub/R-HDB
Engineering	International Engineering Consortium (IEC): www.iec.org/
	Institute of Electrical and Electronic Engineers (IEEE): www.ieee.org/
	IEEE Instrumentation & Measurement Society: www.ieee-ims.org
	Fraunhofer Institute, Germany: https://www.iis.fraunhofer.de/en.html
	Dutch Electronics and Radio Society: www.nerg.nl
	International Amateur Radio Union: www.iaru.org
Regional Organizations	Asian-Pacific Telecommunity (APT): www.aptsec.org
	European Conference of Postal and Telecommunications Administrations (CEPT): www.cept.org
	European Communications Office: https://cept.org/eco
	Inter-American Telecommunications Commission (CITEL): https://www.oas.org/ext/en/main/oas/our-structure/agencies-and-entities/citel
	African Telecommunication Union (ATU): www.atu-uat.org/
	Regional Commonwealth in the Field of Communications (RCC): https://en.rcc.org.ru/

TABLE 7-13 (*end*)

Subject	Description/WWW address
National Organizations	Agence Nationale des Fréquences, France: www.anfr.fr
	Federal Communications Commission, USA: https://www.fcc.gov/
	Federal Network Agency, Germany: https://www.bundesnetzagentur.de/EN/Home/home_node.html
	Industry Canada: www.strategis.gc.ca/spectrum
	Ministry of Communications, Israel: https://www.gov.il/en/departments/ministry_of_communications/govil-landing-page
	Monitoring Earth Station, Leeheim, Germany: https://www.bundesnetzagentur.de/EN/Areas/Telecommunications/FrequencyManagement/FrequencyAssignment/SatelliteCommunications/SatFu/start.html
	National Media and Infocommunications Authority, Hungary: https://english.nmhh.hu/
	National Telecommunication Agency, Brazil: https://www.gov.br/anatel/pt-br
	U.S. National Oceanic and Atmospheric Administration radio user's page: www.ngdc.noaa.gov/mgg/topo/globe.html
	Communications Research Centre (CRC), Canada: https://ised-isde.canada.ca/site/communications-research-centre-canada/en
	National Research Council, Canada: www.nrc.ca
	Ukrainian State Centre of Radio Frequencies and Supervision for Telecommunications: https://www.ucrf.gov.ua/en
	Solar terrestrial activity report (solar Flux/A index chart): www.solen.info/solar/
	Korea Communications Commission, Republic of Korea: https://www.kcc.go.kr/user/ehpMain.do
Scientific Agencies	U.S. National Science Foundation: www.nsf.gov
	Committee on Radio Astronomy Frequencies: www.craf.eu/
	Institute for Telecommunication Sciences: www.its.bldrdoc.gov

CHAPTER 8

Monitoring system planning and tenders

TABLE OF CONTENTS

Page

8.0 Introduction 707

8.1 Topics to be considered by Regulatory Authorities before issuing a tender 707

8.2 General overview of a tender process 708

8.3 Preparation stage: planning 708

8.3.1 Concept for a radio monitoring system 709

8.3.2 Feasibility study 710

8.3.3 Business Plan 711

8.3.4 System planning and design 712

8.3.5 Development of specifications for the system 715

8.3.6 Training 721

8.3.7 Maintenance and repair 721

8.3.8 Documentation 721

8.4 Implementation stage: tender processes 722

8.4.1 Specimen of invitation for monitoring tender 722

8.4.2 Specimen for proposals of the bidder 724

8.4.3 Specimen contract format 726

8.4.4 Evaluation and comparison of proposals and award of contract 728

8.5 Final (termination) stage: Acceptance procedure 729

8.5.1 Factory acceptance 729

8.5.2 Site acceptance test procedure 729

8.6 Final remarks 730

8.7 References 730

Annex 1 to Chapter 8 733

Annex 2 to Chapter 8 738

1 Commercial evaluation – Opening of commercial proposals 738

2 Legal evaluation – Compliance with specimen contract format (Part II of Invitation to Tender) 739

Annex 3 to Chapter *8* 741

1 Scenarios for the development of national spectrum monitoring systems 741

1.1 Short-term scenario 741

1.2 Mid-term scenario 742

1.3 Long-term scenario..... 742

2 Cost-modelling for the development of the spectrum monitoring systems..... 742

3 Lifecycle management considerations related to the spectrum monitoring systems..... 743

8.0 Introduction

As stated in Recommendation ITU-R SM.1392 on essential requirements for a spectrum monitoring system for developing countries, spectrum monitoring systems are often the most expensive parts of a national spectrum management systems whose optimal implementation has a significant economic impact.

The organizational and economic aspects of such implementation are described in detail and comprehensively in this Chapter of the Handbook. No significant materials on this important subject can be found either in other chapters of the Handbook or in any other ITU-R documentation.

8.1 Topics to be considered by Regulatory Authorities before issuing a tender

A National Radio Regulatory Authority has to interpret and implement the provisions of the ITU Radio Regulations (RR), which have the force of international treaty. It has also to implement the national statutory provisions of the national laws and the Rules framed there under, relating to radiocommunications. Compliance of the provisions of the authorisations/ licenses by various wireless users spread all over the country has also been enforced. Monitoring Organization is the field organization of the national authority providing practical data as relevant for spectrum management including control and regulation of wireless networks with a view to ensuring interference-free operations of all networks.

The Monitoring Organization is entrusted with all necessary responsibilities for effecting coherent and extensive usage of radiocommunications in the country. Following aspects relate to planning, coordination and regulation of the spectrum in the national context:

a) optimising the utilisation of radio spectrum by following the latest international standards and practices for spectrum management and wireless monitoring functions;

b) utilisation and protection of orbit/frequency resource for national satellite and other space systems by publishing, notifying and registering national system with ITU and ensuring continued protection from new systems of other countries;

c) identifying the spectrum need for new wireless networks, and assigning to them suitable frequency(ies), power, bandwidth, emission, hours of operation, and other technical parameters with appropriate operational, regulatory and administrative provisions;

d) authorizing the installation and operation of wireless stations by specifying all the necessary technical and operational parameters like frequency of operation, power, emission, hours of operation, etc.;

e) establishing regulations, technical parameters and standards governing the use of each frequency band or specific frequency by stations of different radio services, having regard to current international regulation and agreements;

f) undertaking special coordination work for use of radio systems/equipment in special situations such as natural calamities;

g) maintaining and updating all information on authorized radiocommunication systems such as frequencies, locations of stations, power or call signs.

The main provisions concerning spectrum management are set out in the ITU-R Handbook on National Spectrum Management, which also provides links to relevant ITU-R Recommendations and Reports.

Radio Monitoring supports all these functions as it is an important part of spectrum management process. It plays a significant role in the planning, engineering, electromagnetic compatibility and in ensuring compliance with licensed/authorized parameters. In fact, the monitoring is known as eyes and ears of spectrum management. The tasks and basic requirements for radio monitoring are set out in Chapter 1 of this Handbook on Spectrum Monitoring (further referred as the "Handbook"), as well as in Recommendations ITU-R SM.1050, ITU-R SM.1392 and ITU-R SM.2039.

The other chapters of this Handbook provide many detailed descriptions of all types of monitoring stations, equipment and procedures. They also contain links to relevant ITU-R Recommendations and Reports. This chapter provides an overview about what sort of planning, studies and procedures are required when developing either a nation-wide monitoring system or a fixed or mobile monitoring station. Useful information on this issue is also provided in the ITU-D Guidelines referred in § 8.7.

Radio frequency spectrum is to be used equitably, economically, efficiently and rationally. Appropriate frequency repeatability is therefore required to be ensured. Adoption of appropriate equipment and monitoring system required to be ensured.

8.2 General overview of a tender process

When a national administration decides to create its nationwide monitoring system, a new local monitoring station, or just like take a single mobile measuring system, the work of the established project for the execution of the assigned goal is dividable into three stages (see Fig. 8-1):

Preparation stage: Planning

- Concept for a radio monitoring system
- Feasibility study
- Business plan
- System planning
- Specifications for the systems.

Implementation stage: Tender process

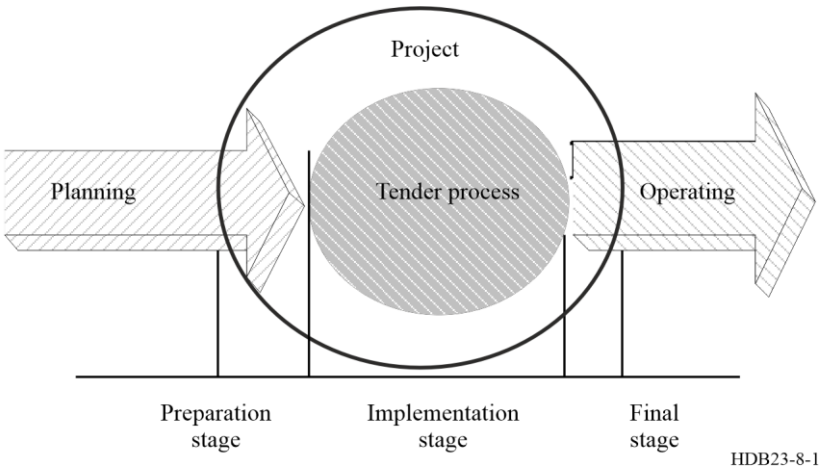
- Invitation to start public purchase tender (consideration of the competence of the bidders, viewpoints of the disqualification for fulfilment of contract)
- Invitation for bids (including clarification to the bidders)
- Submission of proposals by the bidders
- Evaluation of received proposals (request for clarifications inclusive)
- Decision for award of contract
- Signature and entry into force of the contract.

Final (termination) stage: Acceptance procedure, operation

- Factory, provisional and final acceptance procedures
- Training, maintenance and spare parts supply
- Starting up of the operation.

FIGURE 8-1

Three stages of an established project



8.3 Preparation stage: planning

This section describes the various stages, which may lead to a tender process for a complete new monitoring system or part(s) of it, resulting finally to the procurement of equipment.

In case only a part of an existing monitoring system or an individual piece of equipment needs to be replaced, some of these stages are not needed.

In case a complete new monitoring system is needed, a number of fundamental requirements will need to be established in order to come to a monitoring system which responds to the monitoring need of the regulatory body, available budget, etc.

The following stages are described:

- Concept for a radio monitoring system.
- Feasibility study.
- Business Plan.
- System planning and design.
- Development of specifications for the system.

8.3.1 Concept for a radio monitoring system

As described in Chapter 1 of this Handbook, spectrum management is described as the overall process of regulating and administering use of the radio frequency spectrum. The goal of the spectrum management is to maximize spectrum efficiency and minimize interference. Rules and regulations, based on relevant legislation, form a regulatory and legal basis for the spectrum management process. Databases of information, including details of all authorized users of the spectrum, provide the administrative and technical basis for the process. Analysis of the information in these databases facilitates the spectrum management process resulting in decisions for spectrum allocations, frequency assignments, and licensing. Amongst others spectrum monitoring provides the necessary means to maintain the integrity of the spectrum management process and can be defined as a process of observing the radio frequency spectrum and reporting on its use. Automation and integration of a radio monitoring system with an automated spectrum management one is presented in Recommendation ITU-R SM.1537. Issues related to the participation of the planned spectrum monitoring system in the ITU international monitoring system are also subject to consideration (§ 1.6.2 of this Handbook, as well as Recommendations ITU-R SM.1139 and ITU-R SM.1394).

In defining the operational concept, the following elements need to be addressed:

- Automation of data management and spectrum monitoring process, with appropriate computer software. The computer software and equipment for spectrum monitoring activities are specialized as it follows from the ITU-R Handbook on Computer-aided Techniques for Spectrum Management (CAT) and Chapter 4 of this Handbook. Consequently, provision of adequate materials would be essential for these activities.
- Augmentation of automated spectrum monitoring, radio noise surveys and direction finding facilities, both in the fixed and mobile modes (capabilities up to-6 GHz) (various sections of Chapters 3 and § 6.7 of this Handbook).
- If the planned network provides monitoring stations in the HF frequency range, special attention should be paid to determining the number of such stations and their placement throughout the country. This is caused by the specific operating conditions of HF monitoring stations due to ionospheric propagation of radio waves, which requires special approaches. Useful and sufficiently detailed information on the planning and operation of HF radio monitoring networks is provided in [Pavlyuk and Plossky, 2019] and [Chaouachi *et al*., 2021].
- Specialized monitoring facilities for sound and television broadcasting, including measurements of radio coverage areas (§§ 6.2 and 5.11 of this Handbook, as well as Recommendations ITU-R SM.1792 and ITU-R SM.1875 and Report ITU-R SM.2504).
- Specialized monitoring facilities for cellular mobile communication systems, including measurements of the relevant coverage areas (§§ 6.3 and 5.11 of this Handbook, as well as Recommendation ITU-R SM.1447).
- Specialized monitoring facilities for microwave and other higher frequency bands and for specialized services up to 50 GHz or above (§§ 6.4 and 6.5 of this Handbook, as well as Recommendation ITU-R SM.1754 and Report ITU-R SM.2304).

- Augmentation of satellite monitoring facilities for geostationary (GSO) and non-geostationary (non-GSO) satellite systems if this is specified by the planned spectrum monitoring system (§ 6.1 of this Handbook, Recommendations ITU-R SM.1054 and ITU-R SM.1681, Reports ITU-R SM.2182, ITU-R SM.2424 and ITU-R SM.2453).
- Special provisions concerning equipment for measuring non-ionizing radiation in the interests of preventing health hazards caused by electromagnetic radiation (§ 6.6 of this Handbook and Report ITU-R SM.2452).
- The use of commercial drones for spectrum monitoring purposes (§ 3.2.2.3 of this Handbook and Report ITU-R SM.2486).
- The use of spectrum monitoring facilities in the interests of the inspection of radio installations (§ 1.1 of this Handbook, as well as Reports ITU-R SM.2130 and ITU-R SM.2156).
- Structure of the organization (staff) and its interaction with other organizations particularly by the spectrum management (Chapter 1 of this Handbook and Recommendation ITU-R SM.1537).
- Existing and required infrastructure (Chapter 2 of this Handbook).
- Training of personnel for institutional competence and capacity building (Chapter 2 of this Handbook); etc.

These elements are addressed in the following sections.

Once the operational concept has been defined, a cost/benefit analysis should be conducted to assess whether the requirements of the administration would be met in a cost-effective way. This is always necessary, no matter whether a new system or the modernization/modification of an existing system is planned.

8.3.2 Feasibility study

8.3.2.1 The goal of feasibility study

The feasibility study, within the financial and human resources available for this purpose, is a fundamental basis of starting a tender process. The study is needed in order to analyse alternatives, study the impact of developments on the future measurement possibilities and find the best solution, including what would be the impact on the spectrum management responsibilities in case one decides not to procure new equipment.

The study should also answer the question on what the achievable advantages of the technical development are for the authority, the information society and the spectrum users?

During the development of technical planning of monitoring measuring devices or systems, one should take into consideration the technical capability, the lifetime and deterioration of the available devices or systems.

In the course of the planning and development of measurement devices or systems, the following items should be specified and taken into consideration:

- Coverage areas of monitoring based on:
  - i) responsibilities of the Regulatory Body;
  - ii) size of the country;
  - iii) density of the spectrum usage over the country;
  - iv) need for other functional elements of the spectrum management process, such as frequency planning, licensing and enforcement departments;
  - v) responsibility of the monitoring service;
  - vi) future planned use of radio communication in the country.
- Measurement tasks derived from the regulatory environment.
- Technical specification(s) of the equipment related to the tasks.
- Need for a comprehensive measuring system or for a specially designed measuring system for performing a special type of measurement.
- Number and location of (remote) fixed stations.
- The functions of mobile and transportable monitoring units.

- Number and type of mobile and transportable units.
- Purchase of a turn-key system or build-up a system from individual components.
- Integration into an existing system or purchase of a stand-alone system.
- Necessity of remote access to the measurement and/or frequency management data bases.
- Degree of dependence from a single supplier.
- Price of equipment and related cost.

The depth of feasibility studies and the cost for external contributors should be proportional to the value of the investment.

8.3.2.2 Content and structure of the feasibility study

For attainment of the goal of the study, the intended technical purpose, the structure, the implementation procedure, the necessary resources (financial and human), the possible alternatives and the expectable completion date of task must be exactly specified in the study.

The study should specify the topics below in detail:

- Definition of the subject of the study
- Legal and regulatory environment and analysis of the communications market
- Definition of the reason and goal of the study:
  - i) background and justification for the new monitoring system;
  - ii) structure of monitoring system to be implemented;
  - iii) (new) tasks for the monitoring service, including frequency ranges to be covered etc.;
  - iv) existing equipment is outdated and cannot fulfil the required measurements;
  - v) usability and integration of the existing measuring equipment;
  - vi) to provide the monitoring service with technical state-of-the-art system(s);
  - vii) to improve the effective and efficient way of working by the monitoring staff;
  - viii) how many staff is needed to operate a new system;
  - ix) technical competence needed for the staff;
  - x) informatics system and data management;
  - xi) economics calculations (approach to cost-modelling is provided in Annex 3 to this Chapter)
- Alternatives for the implementation of project
- Expectable further developments
- Time schedule for the study
- Resource planning:
  - i) human resource (for the preparatory, implementation and operation stages);
  - ii) financial resources (for the preparatory, implementation and operation stages).
- Management of risks:
  - i) exploration of risk factors;
  - ii) classification of risks;
  - iii) analysis of the effects of risks;
  - iv) on the bases of analyses, elaborating of the appropriate risk management policy.

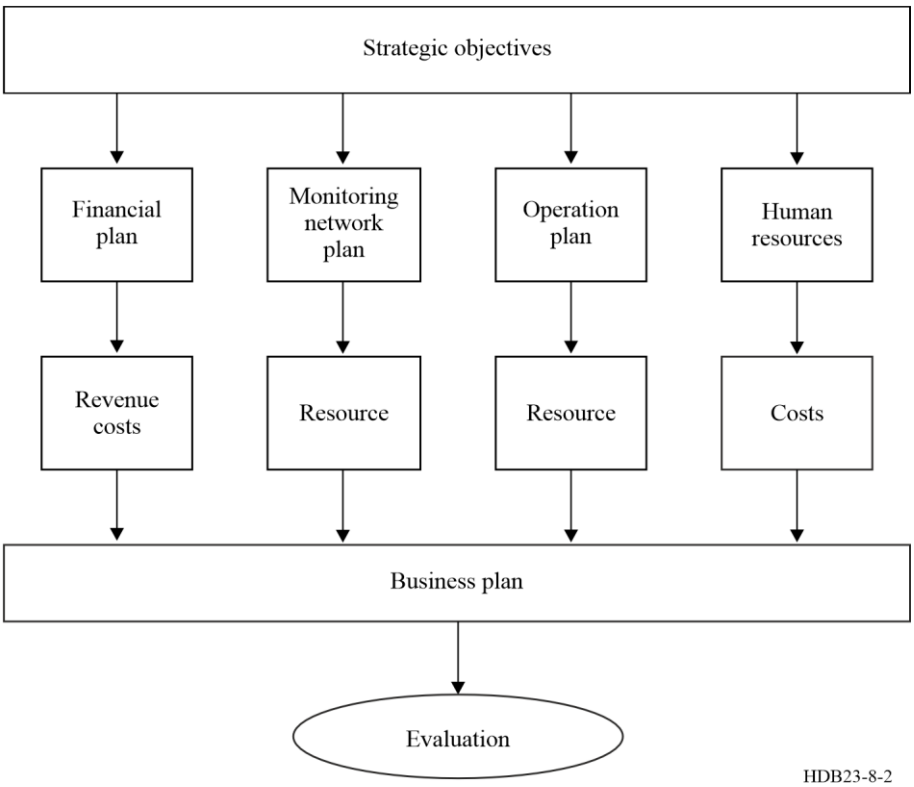
8.3.3 Business plan

A system requirements study is prepared either by the administration or/and by consultants.

A tender may also be necessary in the case of replacement of equipment and in the case that some parts of the process (see Fig. 8-2) have to be modified.

FIGURE 8-2

National management of monitoring business plan



8.3.4 System planning and design

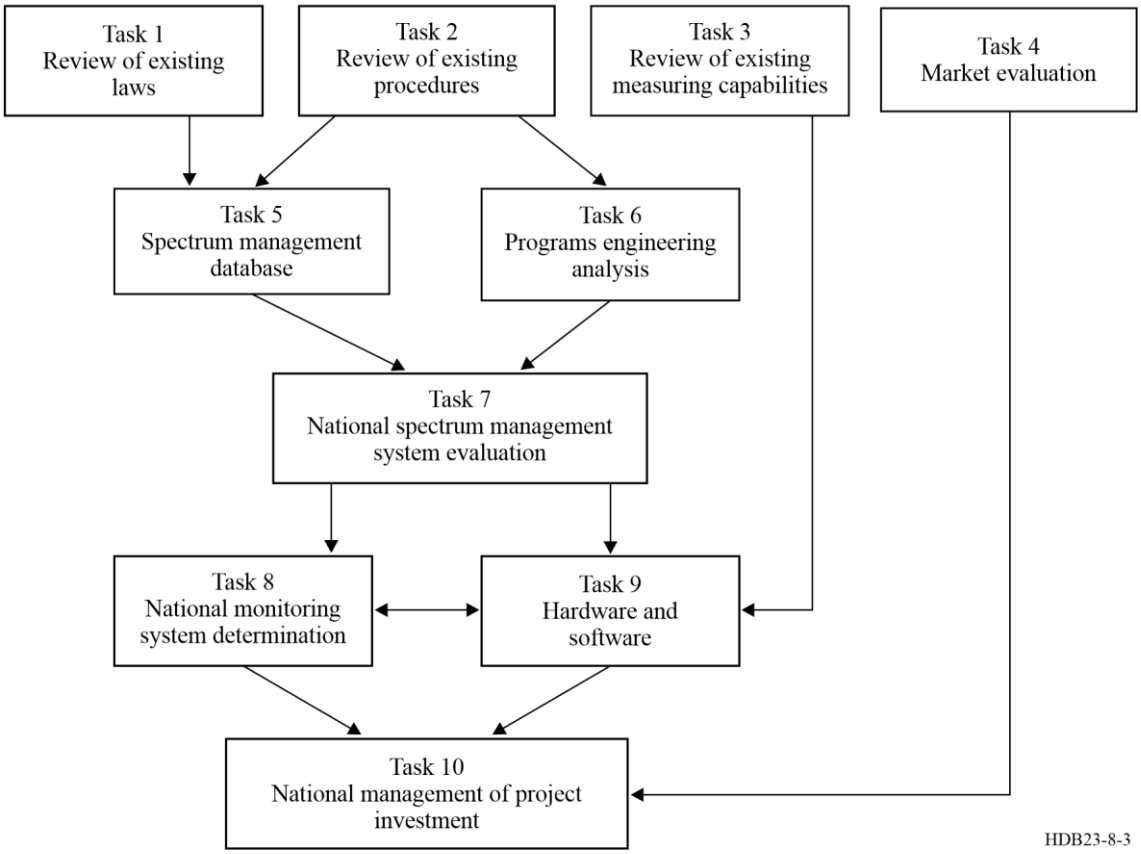
This section proposes a technical approach and a methodology in order to establish a schedule of conditions for the establishment of a national system of spectrum management and monitoring which takes into account the objectives described in the preceding chapters. In the same way, the principle described makes it possible to establish a structure of the management of the spectrum built around basic functions to achieve as described in the ITU-R Handbook on National Spectrum Management.

Some of its functions being able to be gathered or on the contrary subdivided according to the habits, resources of the country considered thus that size of the organization.

Methodology described in Fig. 8-3 is based on ten different tasks taking into account all legal and technical aspects induced by the management of the spectrum in a worldwide environment.

FIGURE 8-3

National spectrum management and monitoring plan



This model tender assumes that land, building construction and utility (water, sewage, telephone, electricity, fuel) connection costs are borne by the Agency issuing the tender.

8.3.4.1 Review of existing laws and legal aspects

Task 1 will make possible that the Administration be familiarized with the new laws and existing billing at the regional, world level and governing the use of the spectrum. Of these allied studies to the knowledge of the national law of the country, an adequate national lawful framework could be established.

8.3.4.2 Review of existing procedures and methodologies

This task will have to be taken into account by the persons in charge of the management and control of the spectrum. It must have reviewed and evaluated the planned organization of the regulator as well as management operations. The framework as well as management operations will have to be considered. A framework will have to be devised that suitably harmonizes requests for licences, the attribution and allowance of frequencies as well as the payments related thereto. This information will be used to develop a data-processing general system corresponding to the needs for management and control of the spectrum.

8.3.4.3 Review of existing measuring capabilities

During the planning phase of development, the capability and suitability of the existing measuring devices must be reviewed. It must be decided which measurement abilities that are sufficient to keep at the present disposal level and which must be improved by the project to satisfy future measurement demands.

The possible integration of newly purchased equipment to the existing system(s) must be also reviewed.

Additionally, the future manpower must be reviewed considering the new measurement tasks.

8.3.4.4 Market evaluation

The use and usability of radio spectrum are essential conditions of the function of communications market. Considering that radio spectrum is a limited natural resource, to satisfy all increasing demands of the communications market is only possible by establishment new modulation technologies (e.g. digital changeover) and opening new frequency bands. When planning the development of a spectrum monitoring system, the developers must be fully aware of the long-term spectrum demands of the communications market, the characteristics of new modulation technologies and the new frequency bands waiting for to be opened. Considering the quick development of measuring systems, efforts should be made to avoid the new system to be obsolete, even shortly after its first operation.

8.3.4.5 Data base of spectrum management

The spectrum management data base will allow the analysis of the data elements in quantity and quality. This is necessary for an effective management of the spectrum in the country. This implies an analysis of the data as well as average existing paper or electronics and their integration in the new information processing system, which will rationalize the information flow and will ensure its storage. (See Recommendation ITU-R SM.1413 – Radiocommunication Data Dictionary for notification and coordination purposes.)

8.3.4.6 Programs engineering analysis

The functionalities and the modules of applications to the engineering necessary are to be determined and should include/understand mainly:

– allowance of the frequencies;

– analyse systems of engineering;

– interference and electromagnetic compatibility;

– calculation of the royalty billing;

– inspection;

– homologation – approval;

– reports/ratios.

These application software modules must be directly inter-connected with the data base of administrative management. Chapter 8 of the ITU-R Handbook National Spectrum Management contains a list of the basic and optional modules required.

8.3.4.7 National spectrum management system evaluation and monitoring system determination

In these tasks, the frequency monitoring capabilities and the requirements for an efficient nationwide monitoring system are determined. The need of a regulatory system ideally requires the establishment of both national and regional administrative offices and various types of monitoring stations. In some instances, the administrative offices and monitoring stations may be accommodated in the same buildings, but not all monitoring stations will have identical facilities.

Some monitoring stations will be required to monitor only VHF/UHF spectrum whilst others will monitor frequencies below VHF and /or above UHF. The location of unknown transmitters and sources of interference will be a major activity requiring suitable direction-finding capability, and this includes mobile stations.

The major objectives of the radio monitoring system are to support the primary activities required for national spectrum management, as well as checking for compliance with the regional and worldwide allocations of the International Telecommunications Union (ITU) and those obtained through bilateral agreement. To be effective, the radio monitoring system must cover all the major population centres throughout the country on a continuous basis. The tasks and activities that must be conducted by radio monitoring system, as well as the necessary equipment are described in this Handbook. The documents will consider the establishment of the technical specifications for and operation of a national regulatory monitoring system. These tasks must consider the existing and/or the development of the Frequency Management Data Base and associated planning software packages that will be required to administer policy.

8.3.4.8 Hardware and software evaluation

According to the needs for data processing (hardware and software) as well as equipment of vehicle inspection expressed in the conclusions for tasks 5, 7 and 8, the experts dedicated to this task must optimize and/or direct the solutions found as well according to criteria of cost as of maintenance/formation.

8.3.4.9 National management of project

At the completion of the network design, the project manager, data engineer and the financial analyst will develop the capital costs and investment requirements for the spectrum monitoring network. It is assumed that a part of the national network can be provided over existing facilities or augmenting the existing capacities. It will be necessary to know the budgetary limitations that the country may impose upon the spectrum programme so that a system concept and specification that is within these constraints may be implanted. In the case of a limited budget, the committee would make recommendations on the time phase programme that would meet the budget requirements and the immediate spectrum monitoring requirements. With this study – Project Investment Brief – the committee prepares a Project Report with tender documents for submission to the national authorities.

8.3.5 Development of specifications for the system

8.3.5.1 Planned spectrum monitoring network, national and regional centres, monitoring stations

In accordance with Recommendation ITU-R SM.1392, when planning a spectrum monitoring system, special attention should be paid to the required number of monitoring stations, the choice of their locations, as well as their remote control. The main provisions on optimizing the placement of monitoring stations in the network are given in § 7.8 of this Handbook, and detailed guidance on this topic is provided in Report ITU-R SM.2356.

The requirements for the placement of monitoring stations in terms of their protection from powerful radio transmitter emissions and from the environmental impact are presented in § 2.5 of the Handbook and in Recommendation ITU-R SM.575. Detailed information on remote control of monitoring stations is given in § 3.8.3.1 of this Handbook.

Administrations in smaller countries tend to have a national monitoring centre and an appropriate number of fixed and/or mobile monitoring stations, which are controlled directly by the national monitoring centre. Administrations in larger countries may find it desirable to have regional monitoring centres in addition to the national centre. In either case, the national monitoring centre may also include a national spectrum management centre to provide integrated automated management and monitoring of the radio spectrum.

The mobile monitoring stations (§ 3.2.2 of this Handbook and Recommendation ITU-R SM.1723) supplement the network of fixed stations although they are indispensable for the purpose of finding sources of radio emissions (including interfering and illegal ones) directly in their locations. Practically, mobile stations have the same measuring capabilities as fixed station, but can be installed easily almost anywhere in the country and, accordingly, are able to monitor different spots. At the same time, it should be taken into account that the operation of mobile stations is more time-consuming and financially costly.

In compliance with their functions, certain mobile monitoring stations (vans for interference investigation, coverage measurement, measurement of microwave networks) possess specialized measurement capabilities. The issues of using transportable stations (§ 3.2.3 of this Handbook) should also be considered.

When specifying their types and necessary number, efforts should be made to achieve their optimal configuration and measurement capacity during the planning stage. Considerations regarding the optimal number of mobile stations relative to fixed stations are given in Report ITU-R SM.2356.

In the case of mobile stations, the expectable frequency of measurement tasks should be taken as a basis in the first place when specifying their necessary number.

During the planning of measurement system capacity, the necessary number of fixed stations depends on the size and the terrain conditions of the area, as well as the frequency range that must be monitored.

When designing a mobile monitoring station, a compromise must be found between full-scale equipment, budget and limitations on weight and space of the vehicle. Therefore, it must be decided whether a general-purpose vehicle or a specialized vehicle for the certain task should be procured.

The available service network and spare part supplies for the applied vehicles in the country are also important viewpoints.

8.3.5.1.1 Organization, number of operator positions and equipment of a monitoring station

The following points will have to be defined:

Control Centre/ Monitoring Station	**Organization/Tasks/Means/Interactions**
Hierarchical position	National/Regional/Local/Other
Allocation of responsibility	Frequency range (e.g. VLF up to HF and/or V/UHF and/or SHF) Services to be monitored, services areas List of monitoring stations to be directly controlled and mobiles List of dependant lower-level control centres
Organization of the work	Existing computer or network architecture (s), software for automation For the number of operator positions, specify: – Operating hours/Numbers of shifts – Hierarchy and share of responsibility between operators – Tasks/Reports/Document follow-up procedures (specify) Archiving methods and means (data, audio, interval …) Reporting means Security concerns and procedures
Work position description	Control all or some of the remote stations' functions Programme or scheduled automated tasks to run off-line in remote stations Perform location computation and display result Access to database to consult technical file of frequency management (interactivity) Display of geographical information Issue automated reports Expected response time (specify for each task) Maximum number of simultaneous connections with remote stations and type of connections (data, voice-grade or broadcast-sound grade audio …) Maximum number of simultaneous recordings (if done at control centre) Man-machine interface: language(s), operation system and data base.
Interaction with frequency management system	Is a computerized frequency management system available? If yes, which one? Is interaction with frequency management system required? Availability of locally available frequency management database
Geographical Information System (GIS)	Which geographical information system is available under which format for integration? 2-D (road map, administrative map, topographic map), vector and/or raster 3-D (digital terrain model) Coordinates to be used (UTM, geographical ...) scales and resolutions, areas required
Communications	a) Means for operators: – Fax/ telephone/Internet (individual or shared) – E-mail (with work positions, control centre(s), station(s), frequency management department etc.) – Radiocommunication means (public, private, HF, VHF/UHF, SHF)

Control Centre/ Monitoring Station	Organization/Tasks/Means/Interactions
	b) Means for remote stations or other control centres – Private networks – Private point to multipoint (radio/microwave/PSTN/ISDN/ Analogue or digital leased lines/X25/VSATs, Internet, …) – Speed and bandwidth

8.3.5.1.2 Measurement tasks

It should be noted that it is up to the responsibility of every country to decide on the measurement tasks and the related frequency ranges to be covered.

To define the essential measurement equipment characteristics for each operator position, the following points should be specified:

Frequency measurement (see § 5.2 of the Handbook)

– Frequency range
– Required accuracy; is a central frequency standard available
– Classes of emission (measurement method).

Field strength, level and power flux-density measurement (see § 5.4 of the Handbook)

– Quantity and methods of measurements at fixed stations, at mobile stations
– Required accuracy
– Frequency range
– Special measurements:
  - Coverage measurements (measurements along a route), measurement of antenna patterns (e.g. by helicopter).

Spectrum occupancy including channel occupancy measurement (see § 5.10 of the Handbook)

– HF emissions, VHF/UHF emissions
– Technical specifications of channels: bandwidth, spacing, type of modulation
– Duration of occupancy recording: continuous, time from … to …, special days, repartition of scans
– Required scanning speed (software)
– Additional information to be recorded (e.g. call sign, automated identification/decoding).

Occupied bandwidth measurement (see § 5.5 of the Handbook)

– β/2 and/or *x*-dB method measurements using spectrum analyser or software
– Other methods.

Modulation measurement (see § 5.6 of the Handbook)

– Modulation depth
– Frequency deviation
– Bit error rate (BER)
– Other quality parameters
– Constellation diagram.

Direction finding and location measurement (see § 5.7 of the Handbook)

– System concept
– Type of station: fixed, mobile, transportable, portable and required accuracy
– Frequency range

– Location (by triangulation or SSL) digital terrain mapping required
– Response time
– Needed space for DF antenna
– Display of bearings on digital maps.

Signal identification (see § 5.8 of the Handbook)

– Classes of emission.
– Identification (e.g. decoding) of the various transmissions
– "Fingerprinting"/"Individual transmitter envelope characteristics".

Monitoring of spacecraft emissions (see § 6.1 of the Handbook)

– Frequency, bandwidth, power flux-density measurements
– Determination of orbital positions
– Occupancy of frequency bands at orbital positions.

Multimedia broadcast (see § 6.2 of the Handbook)

– Terrestrial or satellite services
– Quality of received signal (needs special equipment)/decoding.

Cellular networks to be monitored (see § 6.3 of the Handbook)

– System parameters in order to identify the type of network
– Field strength
– Quality parameters (e.g. RxQual/CIR /BER) (more details on the issues of quality control of cellular networks are presented in several ITU-T Recommendations of the E series, for example, E.806)
– Additional information (e.g. handover for cellular radio)
– Number of channels
– Maximum allowable distance between measurement points
– Maximum distance between the measurement points of the same frequency/channel (valid for all allowed velocities)
– Is a special data evaluation tool needed and is it the intention to combine this system with the mobile monitoring (mapping) system?

Microwave links including satellite links (see § 6.4 of the Handbook)

Receiving and measuring equipment in the 1 to 50 GHz range for which services? (equipment).

8.3.5.2 General equipment specifications

With regard to the elected measurements: to define the equipment allowing these measurements in each monitoring centre, fixed (remote) and/or mobile monitoring station.

a) System concept and architecture centre, station, means of communications, software

The performance of a monitoring station is directly related to the quality of antennas, receivers or field meters and radio direction-finders.

b) Antennas

To determine the types and the number of antennas for each station with regard to the elected, the following details have to be known measurements.

– Basic questions:
  a) Polarization (diversity) and frequency ranges (sub-ranges)
  b) Approximate distances from the region to be monitored (radius)

c) Geographic pointing of the antennas (degrees)

d) Distance between antennas and signal distribution system.

– Signal distribution system:

a) Frequency range

b) Number of receiver connections per antenna

c) Number of antennas if antenna diversity is required

d) Operation of the signal distribution system: manual, semi-automatic or automatic.

– Omnidirectional and dipole antennas:

a) Active receiving antennas

b) Transmitting/receiving antennas

c) Air traffic control antennas.

– Directional antennas:

a) Linearly polarized log-periodic antennas

b) Dual-polarized log-periodic antennas

c) Dish and feed antennas.

For all antennas: frequency range (from 10 kHz to 50 GHz or further); identification of the antenna types in cooperation with the system supplier.

c) Receivers, Direction – Finders

– Frequency bands

– Reception channel number

– Analogue or digital type

– Manual or automatic control (computers, software).

d) Additional equipment

Certain additional equipment will permit more effective operation of a monitoring station. One example is the reporting equipment: reproduction machines, oscilloscopes audio-video recorders, printers, etc.; or:

– Frequency (10 MHz) and time etalon (rubidium, GPS or GLONASS).

– Air conditioner.

For mobile monitoring:

– Navigation and positioning system (Dead Reckoning system, GPS, GLONASS (or other), or a Complex Navigation system).

– Compass for azimuth determination.

8.3.5.3 Monitoring vehicles and devices

The VHF/UHF band mobile monitoring stations shall be designed and supplied housed in a vehicle, and shall be completely equipped with all necessary monitoring equipment, monitoring antennas, modem(s) communication antenna(s), GPS and GPS antenna, interconnecting cables, power supplies, cabinets, racks, mounting hardware, interface devices and terminal blocks to form a complete and working stand-alone system, as well as a reliable component that is an integral part in the national spectrum monitoring system. The vehicle can be also equipped with portable measuring instruments for doing Spot Monitoring or exact interference source localization (see § 3.2.4.1 of the Handbook).

In the course of vehicle purchasing, the following alternatives must be considered:

– Body of vehicle (van, jeep, passenger car)

– Engine type (petrol, diesel)

– Driven wheels (2 or 4)

– Size and weight.

8.3.5.4 Software

The management system and the monitoring system shall contain a significant amount of software to automate data collection, processing, evaluation and interference analysis tasks.

Using software to save spectrum monitoring results in relational databases and correlating this information with the central database of authorized users will save considerable research time while increases the accuracy.

The monitoring application system and control software shall be developed in accordance with the ITU-R Recommendations, in particular ITU-R SM.1537, the ITU-R Handbook on National Spectrum Management 2015, and the relevant ITU-R Recommendations mentioned in this Handbook.

Pieces of monitoring application software:

– Digital mapping software

– Direction finding software (integrated with the mapping software)

– Data base management software

– Intelligent archive system software

– Interface software between licensing database and monitoring measurement results

– Measurement result evaluation software (data filters, post processes and graphically displays of data, automatic reference values and licence database compliance investigation).

The monitoring application program shall be of a user-friendly design, and shall be described in detail in the relevant manuals and guidelines.

8.3.5.5 General requirements for the units of monitoring systems

In the technical annex of invitation for tender document the inviter specifies and publishes the measurement tasks, the required equipment and the expected minimal technical requirements.

During the planning of project implementation, the optimal number of fixed, mobile, portable or hand operated measuring systems and the division of the measuring tasks among them must be decided.

For detailed information on the technical requirements for the units of monitoring systems, see the Chapter 3 of this Handbook.

8.3.5.6 Specifications for services

8.3.5.6.1 Site survey

The location of a fixed radio monitoring system has a very large effect on its efficiency and on the costs that are involved. Siting is governed by geographic, topographic and climatic conditions including local noise and sites must be selected very carefully because this must guarantee the required performance of the overall system.

Generally, the user is responsible for site investigations. Documents, results of measurements, topographical maps, etc. must then be made available, including conclusions on ensuring the protection of future stations from interferences caused by powerful radio transmitters, as well as from the influence of environmental conditions (§ 2.5 of this Handbook and Recommendation ITU-R SM.575).

When developing the systems' operational concept, the number of individual stations and their tasks are decided, and the selection of sites can be made according to § 7.8 of this Handbook and Report ITU-R SM.2356.

In the HF range, sites can be selected by evaluating computerized radio-propagation forecasts, but supplementary measurements should still be carried out on-site. Useful information is also provided by publications [Pavlyuk and Plossky, 2019] and [Chaouachi *et al*., 2021].

8.3.5.6.2 Telecommunication links and network

– Are telecommunication links between the individual stations to be included? If so, of what kind (physical lines, radio links, microwave)? Will the administration provide them? Are telecommunication lines available?

– What is to be transmitted (voice, music, data)?

– Details of lines: type (public dialling network, dedicated network, dedicated telecom line with interfaces according to ITU-T Recommendations (e.g. ITU-T V.24)), quality (transmission rate in bauds, bits/s), length, system (two-wire, four-wire).

– Details of radio or microwave links: frequency, mode, channel bandwidth and transmit/receive system. If available computers are to be integrated into the system, it is necessary to have details of the type, memory capacity, interface conditions, peripherals and software. A transmitter (or transmitters) shall normally be operated remotely to avoid interference to the monitoring station.

– Details of the structure: point-to-point, multipoint-point, ring, star.

– Is masking or encryption required?

8.3.6 Training

In order to make effective use of the monitoring facilities, it is essential that a comprehensive training programme be acquired, along the monitoring facilities. The Bidder shall provide suitable training for the staff in the form of classroom training and on-the-job training, either in the country or abroad. There are two components of this training programme as listed below:

Factory training is to be provided at the supplier's factory on equipment that is identical to that being purchased by the Administration. The classroom training must include a course on the fundamentals of spectrum monitoring (and spectrum management) by suitably qualified trainers with first-hand experience.

Site training will be provided at the Administration's monitoring facilities once the equipment has been installed. Most of the remaining time shall be used for Administration to learn on-the-job increasingly sophisticated monitoring tasks. A final information course shall be provided to show how monitoring information should be utilized to validate national spectrum monitoring.

For training, the number and qualifications of the persons taking part, the location and the duration of the training must be discussed. This calls for separate training courses at different levels.

8.3.7 Maintenance and repair

The concept for maintenance and repair should under all circumstances be developed (e.g. what is to be repaired locally, what centrally and what by the manufacturer(s)?)

Stocking of spares, the considerations to be made are as follows:

a) single components;

b) subassemblies (e.g. circuit boards);

c) whole rack-mounts or plug-ins;

d) critical equipment. (Not forgetting the MTBF – Mean Time Between Failures).

It is also necessary to check the time interval for which the stocking is intended (not forgetting the differing MTTRs – Mean Time To Repair).

8.3.8 Documentation

Equipment/system documentation is provided in the necessary language(s).

Detailed documentation must be available as part of the project. In doing so, the provisions of the following ITU-R Recommendations should be taken into account: ITU-R SM.668, ITU-R SM.1393, ITU-R SM.1809 and ITU-R SM.2117.

8.4 Implementation stage: tender processes

8.4.1 Specimen of invitation for monitoring tender

Depending on the type of tender procedure, the invitation for monitoring tender is an advertisement that invites bidders to submit bids for the implementation of a project.

Usually, national laws prescribe its form, the required contents and the applicable rules of the tender procedure.

The invitation for tender gives a brief description on the project background, the scope of work and the duties of bidders and customer.

This may also contain information on-site inspections and any deadline for clarifications on the Bidding documents.

The technical requirements of monitoring system are detailed in the enclosure of the invitation for tender.

The tender procedures, including the publications, are dependent on the national law.

8.4.1.1 Invitation for monitoring tender document

The invitation for monitoring tender document should include the following:

8.4.1.1.1 Guidance part

This section of the bidding documents provides the information necessary for Bidders to prepare and submit responsive bids that meet the Purchaser's requirements. The guidance part describes the critical steps of bid submission, opening and evaluation, and the stipulations of award of contract.

– Availability data of the Purchaser Administration who issued the invitation for tender to supply and install of the new system.

– Summary (of the project).

– Availability (and sometimes the price) of the technical enclosure of invitation document.

– Instruction for the required format and content of the tender document.

  (Filling out the registration form clearly and legibly is very important as it can be assured only for registered applicants that they receive information on any possible modification, amendment or clarification regarding the contents of the tender document.)

– Stipulations of participation and mandatory prequalification (of Bidders) that they have the financial, technical, and production capability necessary to perform the contract and meet the specified qualification criteria:

  i) Certified references (Experience in handling similar contracts with names of former clients).

  ii) Capabilities with respect to personnel, equipment, and construction or manufacturing facilities.

  iii) Financial and economic stability.

  iv) Quality assurance system.

– Manufacturer's authorisations (if manufacturer is other than supplier).

– Queries.

  Bidders requiring any clarification about the present invitation to tender shall submit their queries by fax or e-mail:

  i) Name(s), address and telecommunications means.

  ii) Deadline for Bidders to submit queries in writing (before the pre-bid meeting).

  iii) Deadline of relevant replies from administration is communicated to all registered Bidders.

– Pre-bid meeting (date, time and place of clarification meeting, generally, not less than three weeks prior to the deadline for submission of bids).

The Bidder shall bear all costs associated with the preparation and submission of its bid, and the Purchaser will in no case be responsible or liable for those costs.

– Technical visit to installation sites:

Two options:

Option 1: Bidders that so desire may conduct a site survey in order to make sure that the equipment it intends to propose match actual tender requirements. The costs of visiting the site or sites shall be at the Bidder's own expense.

Option 2: For many tenders, the purchasing administration requires from the bidders a visit to the sites. For each visited site, the administration delivers an official site report signed by both parts. These documents should be supplied with the offer. Failure of a Bidder to make a site visit is a cause for its disqualification.

– Instructions to Bidders

The bidding documents shall furnish all information necessary for a prospective bidder to prepare a bid for the goods and works to be provided. Bidders are expected to examine all instructions, forms, terms, specifications, and other information in the Bidding documents. Failure to furnish all information or to submit a bid not substantially responsive to the Bidding documents in every respect will be at the Bidder's risk and may result in the rejection of its bid:

i) Submission of proposals:

   a) Address (for submission of bid).

   b) Number of the original and copy tender documents.

   c) Legalize the bid (signed by a person or persons duly authorized to sign on behalf of the Bidder).

   d) Sealing and marking of bids.

   e) Deadline for submission of the bid (any bid received by the Purchaser after the bid submission deadline will be rejected and returned unopened to the Bidder).

   f) Language issues of bid (working language, technical documentation comprising the bid, instruction manuals, software interface, etc.).

ii) Bid formularies.

iii) Prices and currency proposal.

iv) Conformity to international standards and shall meet the latest ITU Recommendations on the subject.

v) Up-to-date design and the use of modern techniques (high standard of performance and reliability).

vi) Delivery.

vii) Guarantees.

viii Specific information to be provided in the proposal.

With regard to national laws and the principles applied by the administration: "Proposals shall contain, but not necessarily be limited, to the following information":

For example:

i) Proposed organization of the work (organizational chart(s), work plan, ...).

ii) Detailed description of the work plan and final products to deliver.

iii) Name and curriculum vitae of all staff assigned to each particular task.

iv) A statement of compliance/non-compliance.

v) Deviations from specifications, in particular if the bidder can prove that the alternative offered will be in all respects as satisfactory and as fully capable of meeting the administration needs as if it conformed fully to the Technical Specifications. The alternative offer must be fully explained.

vi) On-job training. The proposal must clearly indicate: curriculum vitae of the training staff, objectives, target group, desired entrance qualification and number of trainees.

vii) Tender Bond (Tender guarantee, or Bid-Bond).

In this document the Bidder's bank guarantees that in case its client withdraws from the conditions proposed in its bid within its validity period, the bank pays the amount of the guarantee (generally 2 – 5% of the Bidder's proposed price) to the Purchaser Authority.

viii) Performance Bond (will be required only from the winning Bidder).

ix) Validity of the proposals (must be valid for an identified time period after the deadline date for bid submission prescribed by the Purchaser).

x) The original of the technical and commercial proposals shall be signed by an official legally authorized to enter into contract on behalf of the bidder; generally each page of the original shall be witnessed.

– Evaluation of proposals:

i) Opening date, time and scene of the sealed proposals.

ii) Detailed specification of the viewpoints and method for evaluation of bids.

– Disqualification conditions:

i) The offer rejected in case it is incomplete (e.g. Bid Bonds, validity of the offer).

Bids may be rejected in case:

i) After the technical evaluation is shown that one or more of the recommended technical parameters is worse than the minimal requirement in the call for tender document.

The bidders shall be notified of the decision taken, within the indicated date in the tender or the law (by fax, followed by a letter).

8.4.1.1.2 Main articles of the contract

– Subject of contract.
– Obligations of the customer.
– Obligations of the bidder.
– Payment conditions (timing and method of payment).
– Guarantee conditions.
– Procedure in case of violation of contract.
– Procedure in case of force major.
– Procedure for debated cases.
– Managing of confidential information.
– Modification of contract.
– Other instructions.

8.4.1.1.3 Technical requirements

– Subject of the tender.
– System description.
– Inclusions (what the project will include, like software, infrastructure, services).
– Other inclusions (like warrantee, spare parts, software support and update).
– Minimum technical requirements for each parameter of the system and each measuring instruments.

8.4.2 Specimen for proposals of the bidder

8.4.2.1 Introduction

– Introduction of bidder and their experiences.
– Advantages of the proposed system.
– How to meet the proposed system to the future need.

– Ability to be integrated into the costumer's existing system.
– Inclination for taking part in further developments.
– List of proposed sub-contractors.
– Period of validity of bids.

8.4.2.2 General technical characteristics

– Performable measurement tasks (e.g. according to the relevant standards).
– Operating frequency range.
– Accuracy of measured data.

8.4.2.3 System functions

– Feature characteristics of the system.
Information on how they meet to the technical demands of the tender.

8.4.2.4 Method of system implementation

– Denomination of local subcontractors, installation and starting up.

8.4.2.5 Technical guarantees

– Period of guarantees (system, software).
– Provision period for spare parts after guaranteed term.

8.4.2.6 Detailed definitions on:

– Undertaken tasks.
– Presentation of delivered products.
– General system characteristics.
– Technical specifications of each measuring instruments of system.
– Building-up in accordance with requirements.
– Remote and local controlling.
– Data storage and transfer.
– Possibilities on further developments.
– Characteristics of software and integrated with spectrum management.
– Solutions on power supply.
– Types and characteristics of antennas.
– Type(s) and technical data of vehicle(s).
– Health and safety solutions.
– Calibration and self-testing.
– Implementation schedule and deadlines of deliveries.
– Expected tasks from customer.
– Training.
– Arranging of controversial matters.
– Others (e.g. bid for system and software maintenance contracts).

8.4.2.7 Presentation of references

– Financial and economic stability.
– Certified references.
– Quality assurance system.

– Copy of the company registry court document.
– Manufacturer's authorizations.
– List of approved subcontractors.

8.4.2.8 Block diagrams of system

8.4.2.9 Price

– The prices lot-by-lot and the total price.
– Terms and conditions of payment.

8.4.3 Specimen contract format

The contract is a legally binding exchange of agreement between parties that the law will enforce. Breach of contract is recognized by the law and remedies can be provided.

The contract documents must clearly define the scope of work to be performed, the goods to be supplied, the rights and obligations of the Purchaser and of the Supplier or Contractor.

Introductory provisions

– Definition and addresses of the Contracting Parties.
– Preliminaries to the contract.
– Scope, character and purpose of the contract.
– Terms used in the contract.
– Working language.

Legal status of the parties, their rights and obligations

– Rights and obligations of the Supplier:
  i) Sub-contracting.
  ii) Shipping and installation of system and system elements.
  iii) Guarantees.
  iv) Repairing and maintenance of system.
  v) Repairing, maintenance and development of software.
  vi) Related services.
  vii) Training related instructions.
– Rights and obligations of the Costumer:
  i) General instructions.
  ii) Costumer's right to supervision.
  iii) Co-operation obligatory.
  iv) Obligatory of payment.
  v) Training related obligatory.
– Applicable law and the forum for the settlement of disputes.

Subject of the contract

– Subject of the contract.
– Software and the related rights.
– Provisions relating to the completion of the contract.
– Compliance with statues, laws, regulations, etc.:
  i) Installation place and date of completion.
  ii) Method of fulfilment.

iii) Date of completion of the contract.

– Procedure of acceptance:

i) Factory acceptance prior to the acceptance procedure.

ii) General rules for the acceptance procedure of the system.

iii) Place of the acceptance procedure.

iv) Minutes to be drawn up of the acceptance procedure.

v) Acceptance procedure of fixed and mobile stations.

vi) Acceptance of the software and the complete system.

– Packing, shipping and insurance.

– Product upgrades.

– Additional services:

i) Training.

ii) Services to be provided under warranty.

Responsibility for the contracted performance; rules for the impossibility of performance

– Responsibility of the Supplier in case of improper performance:

i) Obligations of the Supplier.

ii) Penalty obligation of the Supplier.

iii) Obligation of the Supplier to remedy the failures.

iv) Warranty obligation of the Supplier.

– The Client's responsibility for the improper performance.

– Impossibility of fulfilment.

Prices and terms of payment

All prices shall include what has been required by the Tender Document.

Fee to be paid for the production, installation of the system as well as the related additional services:

– The total contractual price.

– Payment of the contractual price.

– Additional payment obligations.

Prices shall be quoted excluding taxes, based on national regulations.

Miscellaneous and final provisions

– Obligation of Parties to cooperate, handling of confidential information.

– Settlement of disputes, enforcement of legal rules, governing law.

– Force majeure.

– Amendment to the contract.

– Validity and termination of the contract.

– Other contracts concluded between the Parties.

– Responsible contact persons duly authorized by the Parties.

– Liquidated damages.

– Indemnification.

Annexes to the contract

The annexes to the contract will be based on the procedures from ITU, the World Bank or the purchasing administration.

In all cases the Bid will always be annexed to the contract.

8.4.4 Evaluation and comparison of proposals and award of contract

For the evaluation and comparison of proposals, the purchasing administration needs to follow predefined process of evaluation such as:

– Procedures as defined by the International Telecommunication Union (ITU).
– Procedures as defined by the World Bank.
– Procedures in case the purchasing administration is not bound to the procedures from ITU or World Bank.

A Tender Evaluation committee appointed by the Purchaser authority will evaluate the bids from financial, legal and technical aspects. The evaluation methodology will be defined by the purchasing administration and should be described with all the details in the evaluation report of the Committee.

The proposals submitted by the bidders may be opened in the presence of Bidders' representatives at the stipulated time and place specified in the invitation to bid. Proposal may be rejected if not accompanied by Bid Bond.

During the evaluation the purchasing administration may ask clarifications to the bidders on their offers.

Useful information on evaluating and comparing proposals is provided in the ITU-D Guidelines on tendering process.

8.4.4.1 Procedures as defined by ITU

Evaluation of proposals

– Evaluation group established by ITU or by ITU and the purchasing administration.
– Technical evaluation and commercial evaluation made separately (technical evaluation made first):
  i) The technical evaluation should cover the main following points:
    a) Measuring receiver, antenna system, workstation, software, optional DF system, Factory Acceptance Test (FAT), delivery, training (see Annex 1: ITU example of technical analysis of the proposals).
  ii) The commercial evaluation should cover the main following points:
    a) Price, payment terms and conditions, commercial conditions, legal evaluation (see Annex 2: ITU example of the commercial and legal evaluations).
  iii) Appreciation of technical problems.
  iv) Capability.
  v) Experience of experts.
  vi) Total price.
  vii) Incomplete offers shall be rejected.
  viii) Confidentiality (no information concerning examination, clarification or evaluation shall be communicated to bidders or any other person).
  ix) Bidders shall be notified of decision taken as soon as possible (by fax followed by letter).

Rejection of proposals:

– ITU reserves the right to reject any proposal and call for a second tender.
– No obligation to accept the lowest tender.

8.4.4.2 Procedures as defined by the World Bank

NOTE 1 – The terminology used is that of the World Bank.

When the World Bank (WB), IBRD or IDA, delivers a loan agreement to one of its Members, the WB supplies the borrower in line with a set of documents including Guidelines on procurement of goods, works, and non-

consulting services under IBRD loans and IDA credits and grants by World Bank borrowers (July 2014) and Standard procurement document on request for bids, Information systems (June 2020).

Received proposals are evaluated under the Procurement guidance on evaluating bids and proposals (April 2023) following the general World Bank group evaluation principles (April 2019) using the Standard bid evaluation form for procurement of goods or works (April 1996).

8.4.4.3 Procedures in case the purchasing administration is not bound to the procedures from ITU or World Bank

Before the evaluation starts, the evaluation committee will decide which methodology will be used to decide to which Bidder the contract can be awarded. The following methodologies can be used:

– Scoring approach by use of formulas.

– Weighting method.

– Yes/no compliant.

– Compliant combined with the offered prices.

8.5 Final (termination) stage: Acceptance procedure

8.5.1 Factory acceptance

The provider shall (at its own expense carry out) at the place of manufacture all such tests and/or inspection of the equipment and any part of the equipment as specified in the contract, according to the factory acceptance documents submitted by the provider amended or not by the Administration (Mutual agreement).

8.5.2 Site acceptance test procedure

The provider supplies the site acceptance document(s) to the Administration and shall give a reasonable advance notice of such test and/or inspection and the place and time thereof the project. The tests are carried out to demonstrate that all items of equipment are present; that they are correctly assembled and interconnected; that they function correctly according to the technical specifications (visual inspection and technical tests). A final test of the entire system including the communication links should be carried out taking into account the respective responsibilities for the supplies of the Administration and the contractor.

Acceptance of the system is normally followed by a one-year warranty period, during which the provider may be required to maintain a warranty bond. Alternatively, in some administrations, provisional acceptance is given upon successful completion of acceptance test, and at the conclusion of some period (usually the warranty period) final acceptance is given.

8.5.2.1 Acceptance (or provisional acceptance in the case of provisional and final acceptance)

Acceptance shall occur in respect of the equipment or any part thereof when:

– the acceptance test has been successfully completed and the functional guarantees are met;

– the acceptance test has not been successfully completed or has not been carried out for reasons not attributable to the provider.

Acceptance shall not be withheld if minor discrepancies or problems exist. Rather, acceptance shall occur and the discrepancies and problems shall be noted and corrected during the warranty period.

The following list provides an example of the site acceptance test procedure report's content concerning a HF/VHF/UHF fixed station:

a) Subject

The document describes the acceptance procedures of a Spectrum Monitoring Station under the terms of the contract.

b) Visual inspection

Operations to be carried out to check the presence of all the items listed on the contractual configuration statement and fill in the configurations and handbooks:

– Antennas systems switching, cables, lightning protection.
– Masts, towers (stays, painting, lightning).
– Inspection of building, wiring, security devices, frames, racks, computers, receivers, energy.
– Software implantation.
– Handbooks of equipment, software and system.
– Marking (equipment homologation).
– Documentation will be controlled and the list of the delivered documents annexed to the acceptance report.

c) Technical tests

– Energy check (main supply and UPS).
– HF/VHF/UHF Direction Finding functions: fixed frequency, scanning, location.
– HF/VHF/UHF ITU Measurements: fixed frequency, frequency scanning, memory scanning.
– Signal analysis.
– Manual and automatic missions: systematic control of transmitters, frequency occupation rate, search of unknown transmitters.
– BITE – Build integrated test equipment.

The result of the tests carried out during acceptance will be consigned in the acceptance test report signed by the Administration and the supplier.

8.5.2.2 Final acceptance

In the case of acceptance followed by a warranty period guaranteed by a warranty bond, this section does not apply. In the case of a provisional acceptance followed by a final acceptance, the provisional acceptance certificate signed by both parties, according to the administrative terms specifying the warranty period (generally one year), and after this period the final acceptance certificate is provided.

8.6 Final remarks

The above text concerns a detailed description of the general tendering procedure which can be conventionally called “Equipment/Services and Price Bidding” in its application to spectrum monitoring needs. However, an alternative procedure is also known, called “Fixed Price” or “Lump Sum Biding”, which is widely used, in particular in the construction industry.

A specific feature of this procedure is that the customer in the invitation for tender specifies the minimum required volume of requested equipment and services, and also simultaneously announces the total price of the whole project, which under no circumstances can be exceeded. The winner of the tender is a bidder who offers the maximum volume of equipment and services that the bidder is ready to provide for the specified price, with the mandatory fulfilment of all technical, servicing, organizational, etc. requirements set out in the invitation.

A description of such alternative tendering procedure in relation to the spectrum monitoring needs is provided in [Pavlyuk *et al*., 2023].

8.7 References

ITU-R Publications

NOTE – In every case the latest edition of the ITU document should be used.

Handbooks

Handbook on National Spectrum Management, Geneva, 2015.

Handbook on Computer-aided Techniques for Spectrum Management (CAT), Geneva, 2015.

Recommendations

Recommendation ITU-R SM.575 – *Protection of fixed monitoring stations against interference from nearby or strong transmitters*

Recommendation ITU-R SM.668 – *Electronic exchange of information for spectrum management purposes*

Recommendation ITU-R SM.1050 – *Tasks of a monitoring service*

Recommendation ITU-R SM.1054 – *Monitoring of radio emissions from spacecraft at monitoring stations*

Recommendation ITU-R SM.1139 – *International monitoring system*

Recommendation ITU-R SM.1392 – *Essential requirements for a spectrum monitoring system for developing countries*

Recommendation ITU-R SM.1393 – *Common formats for the exchange of information between monitoring stations*

Recommendation ITU-R SM.1394 – *Common format for Memorandum of Understanding between the agreeing countries regarding cooperation in spectrum monitoring matters*

Recommendation ITU-R SM.1413 – *Radiocommunication Data Dictionary for notification and coordination purposes*

Recommendation ITU-R SM.1447 – *Monitoring of the radio coverage of land mobile networks to verify compliance with a given licence*

Recommendation ITU-R SM.1537 – *Automation and integration of spectrum monitoring systems with automated spectrum management* (E-only)

Recommendation ITU-R SM.1681 – *Measuring of low-level emissions from space stations at monitoring earth stations using noise reduction techniques*

Recommendation ITU-R SM.1723 – *Mobile spectrum monitoring unit*

Recommendation ITU-R SM.1754 – *Measurement techniques of ultra-wideband transmission*

Recommendation ITU-R SM.1792 – *Measuring sideband emissions of T-DAB and DVB-T transmitters for monitoring purposes*

Recommendation ITU-R SM.1809 – *Standard data exchange format for frequency band registrations and measurements at monitoring stations*

Recommendation ITU-R SM.1875 – *DVB-T/T2 coverage measurements and verification of planning criteria*

Recommendation ITU-R SM.2039 – *Spectrum monitoring evolution*

Recommendation ITU-R SM.2117 – *Data format definition for exchanging stored I/Q data for the purpose of spectrum monitoring*

Reports

Report ITU-R SM.2130 – *Inspection of radio stations*

Report ITU-R SM.2156 – *The role of spectrum monitoring in support of inspections*

Report ITU-R SM.2182 – *Measurement facilities available for the measurement of emissions from both GSO and non-GSO space stations*

Report ITU-R SM.2304 – *Application of technical identification and analysis of specific digital signals*

Report ITU-R SM.2356 – *Procedures for planning and optimization of spectrum-monitoring networks in the VHF/UHF frequency range*

Report ITU-R SM.2424 – *Measurement techniques and new technologies for satellite monitoring*

Report ITU-R SM.2452 – *Electromagnetic field measurements to assess human exposure*

Report ITU-R SM.2453 – *Cooperation in the field of space radio monitoring*

Report ITU-R SM.2486 – *Use of commercial drones for ITU-R spectrum monitoring tasks*

Report ITU-R SM.2504 – *Methods for the estimation of coverage for terrestrial radio services based on population*

ITU-D Publications

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Guidelines on Cost Modelling – Economic policies and methods of determining the costs of services related to national telecommunication/ICT networks, Geneva, 2021

ITU-T Publications

Recommendation ITU-T V.24 – *List of definitions for interchange circuits between data terminal equipment (DTE) and data circuit-terminating equipment (DCE)*

Recommendation ITU-T E.806 – *Measurement campaigns, monitoring systems and sampling methodologies to monitor the quality of service in mobile networks*

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Plossky A., Pavlyuk (Pavliouk) A. [2023] *Approach to cost modelling for the development of national spectrum monitoring systems*. Znanstvena misel journal (Slovenia), No. 74. https://www.znanstvena-journal.com/archiv/. The text is available at: www.pavlyuk.com, section «Publications»).

Pavlyuk (Pavliouk) A., Pastukh S., Plossky A. [2023] *Alternative tender process in the field of spectrum management*. Znanstvena misel journal (Slovenia). № 74. https://www.znanstvena-journal.com/archiv/. The text is available at: www.pavlyuk.com, section «Publications»).

Annex 1
to Chapter 8

ITU example of technical analysis of the proposals

TABLE 8-1

Functional parameters	**Specifications**	**Requirements**	**COMPANY Y Basic**	**COMPANY X**
Control	Monitoring and supervision of radio signals	Operational functions, for training purposes	COMPLIANT	Option 1: software only – NOT COMPLIANT Option 2: Hardware + software Only Option 2 is considered below
1 Frequency range of monitoring receiver:	Frequency range: 100 kHz – 2.5/3 GHz	The frequency range must include all radio services operated in the bands indicated	COMPLIANT	COMPLIANT with some reservations (see observation on last row)
2 Receiving antennas:	Frequency range: 100 kHz – 2.5/3 GHz	In accordance with the system's characteristics	COMPLIANT	COMPLIANT
3 Operating modes:	Manual and automatic	The system must make it possible to differentiate between manual and automatic monitoring	COMPLIANT	COMPLIANT
4 Measurement of technical signal parameters:	1 Frequency 2 Field strength and power flux-density 3 Bandwidth 4 Modulation percentage (AM) 5 Frequency offset (FM) 6 Spectrum analysis 7 Spectrum occupancy measurements	– Measurements in accordance with ITU-R Recommendations and RR – Real-time and differentiated measurements – Interception, demodulation, recording and analysis of signals – Free determination of the threshold for signal reception	COMPLIANT	COMPLIANT
5 Demodulation:	CW, AM, FM, SSB, NFM, WFM		COMPLIANT	COMPLIANT

TABLE 8-1 (*end*)

Functional parameters	Specifications	Requirements	COMPANY Y Basic	COMPANY X
6 Tracking functions:	1 Discrete frequency tracing 2 Frequency tracking by band 3 Discretionary selection of frequency steps	Manual and automatic frequency selection	COMPLIANT	COMPLIANT
7 Data collection:	Storage of measurement results and generation of reports	Interface for connection of peripheral equipment such as printers and PCs	COMPLIANT	COMPLIANT
8 Application software:	1 Man-machine interface: – User-friendly – Clearly identified functions – Frequency spectrum – Easy reading of results – Conversion of units – Visualization of statistical occupancy tables 2 Simulation of the radio direction-finding process 3 Potential growth of the system: – Ability to install radio direction-finding equipment easily – Easy to maintain – Automatic testing – Easy to use – Versatile		COMPLIANT	COMPLIANT

TABLE 8-2

Functional parameters	**Specifications**	**Requirements**	**COMPANY Y Basic**	**COMPANY X**
Training	1 Course on assembling an installation 2 Course on operation and maintenance 3 Guidance material for training (in printed or electronic form)	Five days for two engineers. Course No. 1 will take place at the factory Course No. 2 includes the preventive and corrective maintenance	COMPLIANT	NOT COMPLIANT
Vocabulary of terms, acronyms and abbreviations	Both in English and French	Optional: Spanish	COMPLIANT	COMPLIANT
Power supply	220V ± 5%, 50 Hz		COMPLIANT	Not indicated
Documentation	1 Installation plans 2 Operational and maintenance manuals of both the system and its components	Conceptual diagram of the system Description of systems and equipment Assembling and installation plans Operational acceptance test-run of the station Procedures to carry out detection and correction of system flaws Operational procedures for corrective and preventive periodic maintenance Procedures to locate system breakdowns and repair thereof	COMPLIANT	COMPLIANT
Supply of goods and services	The contractor will assume the responsibility for providing goods and services as established in the respective contracts		*	
Support and spares	Supply of pieces and spare parts (fungibles and non-fungibles) necessary for the maintenance service of the system for a two-year period after the final acceptance of the contract		*	10 years after the final acceptance
Factory acceptance test	Verification of technical specifications of the equipment		One ITU specialist, three working days	No indication concerning factory acceptance test

TABLE 8-2 (*end*)

Functional parameters	Specifications	Requirements	COMPANY Y Basic	COMPANY X
Transportation and delivery	A maximum of [180] days on site, including the responsibility of packing, transportation and installation		*	Four months after the order. Delivery in Geneva
Installation	It is the responsibility of the contractor to install the equipment and carry out all required tests to guarantee the perfect condition and functioning of the system	Installation, testing, integration and operation	*	
Running of provisional tests before acceptance	To test the reliability of the installation and functioning of the system and the equipment		*	
Running of final tests before acceptance	Protocol of acceptance		*	COMPLIANT
Guarantee	Guarantee of quality covering the smooth functioning, material and software for 12 months after the date of final acceptance		*	COMPLIANT

* Note 1 – Compliant according to statements made by COMPANY Y in “compliance list”.

TABLE 8-3

Functional parameters	**Specifications**	**Requirements**	**COMPANY Y Basic**	**COMPANY X**
The insurance responsibility	The contractor signs an insurance policy to cover any risk that can arise until the certificate of provisional acceptance has been issued (covering the period from the moment when the equipment leaves the factory until its provisional installation, where it has been delivered)			
1 Overall presentation of technical part 2 Computer workstation (Item 2 of terms of reference)			1 Very good 2 OK **List of options:** …	1 Poor presentation of the offer and difficulty to find the appropriate/relevant information 2 Workstation: minimum configuration 3 No Factory acceptance test 4 Training: proposal not compliant with the ToR

Annex 2
to Chapter 8

ITU example of the commercial and legal evaluations

1 Commercial evaluation – Opening of commercial proposals

1.1 The total opening price of each of the offers as identified by the Evaluation Group is as follows:

Bidders (in alphabetical order)	Total opening price in USD
Company X	[999 999.00] – 1st proposal [999 999.00] – 2nd proposal
Company Y	[999 999.00] – basic proposal [999 999.00] – optional proposal

1.2 COMPANY X submitted the most comprehensive commercial proposal. COMPANY Y provided most of the required information in its offers. However, the level of detail (e.g., price breakdown) was not satisfactory and consequently required further clarifications.

1.3 The Total Evaluated Price (TEP) of each of the two offers as identified by the Commercial Evaluation Committee is as follows:

Bidder	Basic proposal	Optional proposal 1	Optional proposal 2
COMPANY X	USD [999 999.00]	USD [999 999.00]	USD [999 999.00]
COMPANY Y	USD [999 999.00]	USD [999 999.00]	–

1.4 No detailed price breakdown was presented by COMPANY Y. Consequently, it was necessary to require a detailed explanation of its overall price in order to complete the commercial evaluation of its proposal. COMPANY X did not provide the complete required information (a detailed price breakdown list of items for Options 1 and 2).

1.5 COMPANY X and COMPANY Y are considerably different in their respective opening prices. In the case of COMPANY X, the most significant difference comes from the fact that the basic proposal contains only training. Consequently, following the recommendation of the TEC., for more details please see TEC's Technical Evaluation Report.

1.6 Prices quoted by … contain a 10% discount of the item total price.

1.7 Price is in USD CIP Geneva (taking into consideration that ITU did not identify the point of destination). ITU needs prices quoted DDU – in accordance with Incoterms 2000 including customary packing (point of destination to be determined). This point has to be clarified during the negotiation contract.

1.8 ***Payment terms and conditions***. Both companies have proposed payment terms. Therefore, payment terms and conditions of the future contract ***need to be negotiated*** with the selected company.

1.9 Both offers include ***commercial conditions***. In the case of contract negotiations with both companies, ITU may discuss all proposed modifications and additional payment conditions of the Contract in accordance with ITU rules and regulations (see for COMPANY X pages ii to jj of Chapter N of the commercial proposal and for COMPANY Y proposal pages kk to ll of Chapter M).

2 Legal evaluation – Compliance with specimen contract format (Part II of Invitation to Tender)

General information	**COMPANY X**			**COMPANY Y**	
	1st proposal	**2nd proposal**	**3rd proposal**	**1st proposal (basic)**	**2nd proposal**
Proposal validity					
Compliance with contract	Yes (α)	Yes	Yes	Yes	Yes
Compliance with technical requirements	Yes	Yes	In addition	No	Yes
Total man/days	5	5	–	–	15
Total working time	7.5 h/day 3-5 days	7.5 h/day 3-5 days	–	9 h/day 2 days	9 h/day 6 days/4 weeks
Price per man/day	9 999.00	9 999.00	–	–	9 999.00
Total man/days	6	6		10	10
Total working time	7.5 h/day 5 days (37.5 h)	7.5 h/day 5 days (37.5 h)		6 h/day 1 day (6 h)	6 h/day 5 days/3 weeks (90 h)
Price per man/day	9 999.00	9 999.00		9 999.00	9 999.00
Elements that may increase the total firm fixed price	None, if items are restricted to items Price Schedule I to III submitted with the offer	None, if items are restricted to items Price Schedule I to III submitted with the offer		Training classroom and equipment not available	Training classroom and equipment not available
Counterpart services the bidder expects will be provided by ITU	Appropriate installation site must be provided	Appropriate installation site must be provided		Set up classroom and make sure necessary training equipment is available	Set up classroom and make sure necessary training equipment is available
Commitment to start and perform work	Effective date of contract	Effective date of contract		Effective date of contract	Effective date of contract
Time of delivery/ conditions	*N* month	*N* month		*M* weeks	*L* weeks
Total firm fixed price in USD					

2.1 α – Concerning the compliance with requirements:

COMPANY X remarks that:

i) The translation of the system software into the French language is offered separately, since all our customers worldwide do accept the software in the English language.

ii) Translation of software into French requires a one-time charge.

iii) The manuals for equipment and training will be provided in French.

iv) Training for preventive and corrective maintenance will be provided, if trainees have engineering degrees and experience.

COMPANY Y second proposal (optional) fully complies with the requirements.

2.2 With regards to the proposed ***Specimen Contract Format***. In the case of contract negotiation with both companies, ITU may discuss all proposed modifications and additions to Specimen Contract Format and payment conditions. The most important concern the following articles:

a) **Substantive law** (compliance with statutes, laws, regulations):

COMPANY X proposes that "all disputes shall be settled in accordance with the terms of the contract and the supplementary agreements, otherwise in accordance with the substantive law in force in the country XYZ without referring to other substantive laws".

This requirement is not in accordance with ITU rules and regulations.

NOTE 1– Declare "comply" with Specimen Contract Format.

b) Arbitration:

COMPANY X proposes that "the attempt shall be regarded as being miscarried, if one of the two parties informs the other party of this fact in writing". If an attempt at settlement has failed, the disputes shall be settled under the Rules of Conciliation and Arbitration of the CCI in [CITY] by three arbitrators... (see page k/k, Chapter *N* of the commercial part) – This article could be negotiated.

c) Factory inspection acceptance and delivery:

See comments/proposal of COMPANY X, paragraph *n,* page *m* of Chapter *N* of the optional proposal.

d) Guarantees:

Both companies give detailed conditions of guarantee and request modifications. Some of the proposed modifications are not in accordance with the ITU standard contract but could be negotiated.

e) *Force majeure:*

COMPANY X suggests modifying this article. See Chapter *N*, page *i/k* "…the event of *force majeure* shall be confirmed by the Chamber of Commerce, ...". Some of the proposed modifications are not in accordance with the ITU standard contract but could be negotiated.

Annex 3
to Chapter 8

Approach to cost-modelling for the development of spectrum monitoring systems

Cost-modelling is the process of estimating the costs of a project, product, service, or activity based on various factors and assumptions. More information on cost-modelling in the field of telecommunications/ICT could be found in ITU-D Question 4/1 Guidelines on cost modelling: Economic policies and methods of determining the costs of services related to national telecommunication/ICT networks.

1 Scenarios for the development of national spectrum monitoring systems

For the purpose of economic planning and cost-modelling for the development of spectrum monitoring systems, the necessary actions divided by three scenarios [Plossky and Pavlyuk, 2023]:

- Short-term scenario;
- Mid-term scenario; and
- Long-term scenario.

1.1 Short-term scenario

The short-term scenario is the initial one for consideration of any spectrum monitoring system development, because it is mainly focussed on the utilization of existing stations and equipment. In case of scarce of existing financial, human and technical resources this is the only appropriate scenario to be applied. Over the scenario which could be conducted in the short-term period (usually up to 2 years), two typical actions can be implemented:

– System project;

– Minor upgrading existing spectrum monitoring stations.

System project usually consists of three stages:

– Initial assessment. At this stage regulator conduct assessment of existing spectrum monitoring system, including in-field testing and monitoring coverage evaluation using appropriate software;

– Setting the goals for development of spectrum monitoring systems. At this stage regulator sets the goals for spectrum monitoring system considering available finance, human and technical resources.

– Conducting the project. At this stage regulator with the help of specific monitoring coverage software and using the internationally-recognized procedures. They should also include the estimation of capital expenditures (CAPEX) and operating expenditures (OPEX) for the different timeframes of the project.

Considering the usual difficulties for developing countries to acquire new core equipment for spectrum monitoring system, upgrades for existing monitoring stations usually consist of:

– shifting existing monitoring stations for new places to provide better monitoring coverage;

– adjusting the heights of monitoring antennas for the same reason;

– utilization of spare or optimization of using the whole existing equipment, which may be used, to create new fixed/mobile/transportable or update existing monitoring stations;

– improving engineering systems/facilities (e.g. air conditioning, data exchange network, physical security).

These actions could be done after conducting abovementioned system project, which includes the monitoring coverage optimization by software calculations and in-field assessments.

1.2 Mid-term scenario

Possibly conducting together with or just after short-term scenario, this is the core scenario for undeveloped or absent spectrum monitoring systems. Over the scenario which could be performed in the mid-term period (two to five years), there are two typical actions:

– Acquiring and installing new monitoring stations for spectrum monitoring systems both fixed and mobile ones to cover major cities and economically attractive zones;

– Major upgrading the existing spectrum monitoring stations, for example, replacing non-interoperable monitoring equipment before depreciation period is over.

1.3 Long-term scenario

This scenario conducts over the period of five to ten years and includes the flowing actions:

– Further acquiring and installing new monitoring stations for spectrum monitoring system both fixed and mobile (including handheld) ones to cover the major part or the whole territory of the country;

– Replacing of outdated existing monitoring equipment whose depreciation period is over.

2 Cost-modelling for the development of the spectrum monitoring systems

Considering the above-mentioned scenarios for the spectrum monitoring system development, cost-modelling should be conducted upon the system project stages of the short-term scenario. Setting the right goals for spectrum monitoring system development should be based on the proper estimation of project's cash-flow and sustainable cost-model using the following algorithm:

2.1 Step 1. Estimation of CAPEX cost of new monitoring stations

By this stage regulator using the data on the costs estimates the average equipment cost of fixed and mobile monitoring stations and associated services. This estimation includes:

– core monitoring equipment and supplementary engineering systems (conditioning, exchange network, security, etc.);

– related construction works, including installation and transportation of monitoring equipment,

– antenna masts and shelters installation;

– civil works, if necessary, including building construction and rod lying, provision of water supply and sewerage;

– commissioning works including connection to broadband communication and electric networks;

– installation of security, alarm and lightning protection systems;

– checking, testing and tuning the hardware and software, including conformance & interoperability testing;

– warranty and after warranty services, etc.

This is the core expenses for mid-term and long-term scenarios, but in case of shifting the existing monitoring stations for new places, construction and commissioning work calculations for short-term scenario can be used.

2.2 Step 2. Estimation of cost of antenna masts

By this stage regulator using the data on the costs of metal constructions for the different heights of antenna and costs of foundation, including the costs of transportation and construction works estimates the reference configuration of antenna masts for existing fixed monitoring stations for CAPEX of any scenario and estimates the cost of shifting the existing monitoring stations for new places and increasing the heights of monitoring antennas if these actions considerably increase motoring coverage of stations.

2.3 Step 3. Calculation of cost for short-term scenario

Considering the assumption that short-term scenario actions will not usually imply the expanding the monitoring staff and increasing the general maintenance cost, the system project and minor upgrades the existing spectrum monitoring stations require only CAPEX.

2.4 Step 4. Evaluation of needs in changing the number of existing monitoring staff

By this stage regulator using the data on the existing monitoring staff and statistics on the correlation between the total number of monitoring stations and the number of staff, estimates the OPEX related to the necessary expansion of different categories of monitoring staff for mid-term and long-term scenarios.

2.5 Step 5. Estimation of increase the OPEX for spectrum monitoring system

By this stage regulator using the data on OPEX for existing spectrum monitoring system estimates the additional OPEX for mid-term and long-term scenarios, including depreciation deductions, maintenance fees, connection fees, electricity fees, rental costs and salaries of staff.

2.6 Step 6. Calculation of cost for mid-term and long-term scenarios

By this stage regulator using the data acquired at previous steps estimates the CAPEX and OPEX for mid-term and long-term scenarios.

2.7 Step 7. Additional calculations

Additional calculations could consist of the investment plans based on the year-by-year available finance resources, price adjustments on new financial inputs, changes in setting goals for the development of spectrum monitoring system, depreciation costs, e-waste utilization/management (referring to discarding of out-of-date or broken spectrum equipment without intent of re-use or with partial re-use. See https://globalewaste.org/ partnered by ITU), decommissioning, etc.

3 Lifecycle management considerations related to the spectrum monitoring systems

The abovementioned development scenarios and cost-modelling steps could be considered by regulators as a simplified guideline for lifecycle management of spectrum monitoring systems, including the following stages of lifecycle:

– planning stage (short-term scenario, project phase; relates to CAPEX);

– procurement and deployment stage (all of scenarios, depending on the needs and available resources; relates to CAPEX);

– provision stage (mid-term and long-term scenarios, considering only the necessary changes in comparison with existing spectrum monitoring system; as relates mainly to OPEX);

– optimization stage (second cycle of development, so regulator will start again from short-term scenario);

– decommissioning stage (out of development scenarios).

It is necessary to note that a common tender process for spectrum monitoring system development does not include optimization and decommissioning stages, but a regulator could consider the additional cost as referred to in item 2.7 of this Annex and/or includes decommission works for outdated or broken equipment in the tender for the deployment stage.

List of the abbreviations used in the Handbook

3G	3rd Generation of cellular network technology
3GPP	3rd Generation Partnership Project
4G	4th Generation of cellular network technology
5G	5th Generation of cellular network technology
A/D	Analogue to digital
AAC	Advanced audio coding
AAS	Advanced antenna system
ABW	Acquisition bandwidth
AC	Alternating current
ACLR	Adjacent channel leakage ratio
ACPR	Adjacent channel power ratio
ACS	Auto configuration server
AGC	Automatic gain control
AI	Artificial intelligence
AIS	Automatic identification system
AM	Amplitude modulation
AMC	Automatic modulation classification
AMDS	AM data system
AMSL	Above mean sea level
AOA	Angle of arrival
API	Application programming interface
ARIB	Association of Radio Industries and Businesses
ASK	Amplitude shift keying
ASMS	Automated spectrum management system
ATIS	Automatic transmitter identification system
AV	Average (referring to the Average-Detector)
AVD	Automatic violation detection
Az/El	Azimuth-Elevation
BaaS	Back-end as a Service
BCCH	Broadcast control channel
BDT	Telecommunication Development Bureau
BER	Bit error rate/ratio
BIST/BIT	Basic instrument self-test
BIT	Built in test
BITE	Build integrated test equipment
BLER	Block error rate
BLOB	Binary large object
BPSK	Binary phase shift keying
BR	Radiocommunication Bureau
BR IFIC	BR International Frequency Information Circular
BRF	Band rejection filter
BS	Base station

BTS	Base transceiver station
BW	Bandwidth
C0	A GSM BS uses at least one RF frequency, called C0
CA	Channel arrangement
CAE	Carrier acquisition equipment
CAF	Cross ambiguity function
CAPEX	Capital expenditures
CAT	Computer aided techniques
CB	Citizen band
CCDF	Complementary cumulative distribution function
CCI	Chamber of Commerce and Industry
CDF	Cumulative distribution function
CDMA	Code division multiple access
CEPT	European Conference of Postal and Telecommunications
CIP	Carriage and insurance paid to
CIR (Chapter 5)	Channel impulse response
CIR (Chapter 6)	Committed information rate
CISPR	Comité international spécial des perturbations radioélectriques
CLI	Command line interface
CNN	Convolutional neural network
CODATA	Committee on Data of the International Science Council (European Commission Expert Group)
COFDM	Coded orthogonal frequency division multiplex
CPLPA	Circularly-polarized log-periodic antenna
CPM	Continuous phase modulation
CRC	Cyclic redundancy checksum
CSS	Chirp spread spectrum, such as used by IEEE 802.15.4a
CTCSS	Continuous tone coded squelch system
CW	Carrier wave / Continuous wave, synonymous for N0N
DAB	Digital audio broadcast
DAM	Dynamic amplitude modulation
DANL	Displayed average noise level
DARC	Data radio channel
DBSCAN	Density-based spatial clustering of applications with noise
DC	Direct current
DCE	Data circuit-terminating equipment
DCMI	Dublin core metadata initiative
DDC	Digital down-converter
DDU	Delivered duty unpaid
DECT	Digital enhanced cordless telecommunications
DEM	Digital elevation model
DF	Direction-finding, Direction-finder
DIFI	Digital intermediate frequency interoperability
DL	Deep learning
DME	Distance measuring equipment
DOA	Direction of arrival

DRAM	Dynamic random access memory
DRM	Digital Radio Mondiale
DSM	Dynamic spectrum monitoring
DSP	Digital signal processor/processing
DSSS	Direct spread sequence spectrum
DTE	Data terminal equipment
DTF	Distance to fault
DTM	Digital terrain model
DTMF	Dual tome multiple frequency
DTSB	Digital terrestrial sound broadcasting
DTTB	Digital terrestrial TV broadcasting
DVB-T	Terrestrial digital television
e.i.r.p.	equivalent isotropically radiated power, see RR No. **1.161**
E.M.F.	Electromagnetic field
e.r.p.	effective radiated power, see RR § 1.162
EC-GSM-IoT	Extended coverage GSM IoT
ECU	Electronic control unit
EDGE	Enhanced data rates for GSM evolution
EDM	Event driven monitoring
EESS	Earth exploration-satellite service
EHF	Extremely high frequency (30 to 300 GHz)
EIA	Electronic Industries Association
EMC	Electromagnetic compatibility
EMF	Electromagnetic field
epfd	Equivalent power flux-density
EVM	Error vector magnitude
F_a	Noise figure (external noise power above thermal noise in dB as in Recommendation ITU-R P.372)
FaaS	Function-as-a-service
FAIR	(principles) Findable, accessible, interoperable, reusable
FAT	Factory acceptance test
FBO	Frequency band occupancy
FCO	Frequency channel occupancy
FDD	Frequency division duplex
FDM	Frequency division multiplex
FDMA	Frequency division multiple access
FDOA	Frequency difference of arrival
FEC	Forward error correction
FER	Frame error rate
FET	Field effect transistor
FFT	Fast Fourier transform
FHSS	Frequency hopping spread spectrum
FIFO	First-In, First-Out
FM	Frequency modulation
FPA	Flat panel antenna

FPGA	Field-programmable gate array
FR	Frequency range
FSK	Frequency-shift-keying
FTL	Faster than light (Protocol)
GDAL	Geospatial data abstraction library
GDOP	geometric dilution of precision
GFT	Goodness of fit test
GIS	Geographic information systems
GIS	Geographical Information System
GLONASS	Global navigation satellite system
GMM	Gaussian mixture model
GMSK	Gaussian minimum shift keying
GNSS	Global navigation satellite system
GPS	Global positioning system
GSM	Global system for mobiles
GSO	Geostationary-satellite orbit
GUI	Graphical user interface
HDF5	Hierarchical data format, version 5
HF	High frequency band (3 to 30 MHz), see RR No. **2.1**
HH	Handheld
HLS	HTTP live streaming
HSDS	High speed data system
I/Q, IQ	Inphase-/Quadrature
IaaS	Infrastructure as a service
IAM, IdAM or IdM	Identity and access management
IANA	Internet Assigned Numbers Authority
IBRD	International Bank for Reconstruction and Development
IBW	Instantaneous bandwidth, integration bandwidth (depending on context)
ICMP	Internet control message protocol
ICNIRP	International Commission on Non-Ionizing Radiation Protection
ICPM	Incidental phase modulation
ICT	Information and communications technology
IDA	International Development Association
IDWM	ITU digitized world map
IEC	International Electrotechnical Commission
IF	Intermediate frequency
IFL	International frequency list
IFM	Instantaneous frequency measurement
ILS	Instrument landing system
IM	Intermodulation
IMD	Intermodulation distortion
IMP	Intermodulation products
IMT	International mobile telecommunication
IN	Impulse noise
IoT	Internet of things

IP (Chapter 3, other Sections)	Intercept point
IP (Chapter 3, Section 3.8)	Internet protocol
IS95	Interim Standard 95 (first CDMA-based digital cellular radio standard)
ISB	Independent sideband
ISDN	Integrated services digital network
ISI	inter-symbol-interference
ISM	Industrial, scientific and medical
IT	Information technology
ITU	International Telecommunication Union
ITU BR	ITU Radiocommunication Bureau also referred to as the Bureau
ITU-D	ITU Telecommunication Development Sector
ITU-R	ITU Radiocommunication Sector
ITU-T	ITU Telecommunication Standardization Sector
KIS / KISS	Keep it simple
LAN	Local area network
LCD	Liquid crystal display
LED	Light emitting diode
LF	Low frequency band (30 to 300 kHz), see RR No. **2.1**
LLM / LLMs	Large language model(s)
LNA	Low noise amplifier
LO	Local oscillartor
LoB	Line of bearing
LoS	Line of sight
LPA	Log-periodic antenna
LPCM	Linear pulse-code modulation
LSB	Lower side band
LSTM	Long short-term memory
LTE	Long term evolution
LTE-M	Long term evolution for machines
M&C	Monitoring and control system
MCP	Model context protocol
MER	Modulation Error Ratio
MF	Medium frequency band (300 to 3 000 kHz), see RR No. **2.1**
MFN	Multi-frequency networks
MIMO	Multiple-input multiple-output
ML	Machine learning
MMIC	Monolithic microwave integrated circuit
MMN	Man-made noise
MoU	Memorandum of understanding
MPX	Multiplex signal
MRCF	Maximum rate of change of frequency
MSC BER	Main service channel bit error rate
MSK	Minimum shift keying

MTBF	Mean time between failures
MTTR	Mean time to repair
MUSIC	Multiple signal classification
NAT	Network address translation
NB-IoT	Narrowband IoT
NCM	Network configuration management
NF	Noise figure
NFM	Narrowband frequency modulation
NLP	Natural language processing
NMEA	National marine electronics association
non-GSO	Non-geostationary-satellite orbit
NR	New radio
NR, 5G NR	New radio (Air interface of 5G)
OATS	Open air test site
OFDM	Orthogonal frequency division multiplexing
OFDMA	Orthogonal frequency division multiple access
OGC	Open geospatial consortium
OMT	Orthomode transducer
OoB	Out-of-band
OOK	On-off-keying
OPEX	Operational expenditures
ORC	Optimized row columnar
OS	Operational system
OWL	Web ontology language
PaaS	Platform as a service
PAM	Privileged access management
PC	Personal computer
PCA (Chapter 4)	Principal component analysis
PCA (Chapter 6)	Position of closest approach
PDCA	Plan, do, check, act
PEP	Peak envelope power
pfd	power flux-density
Pk	Peak (referring to the peak-detector)
PM	Phase modulation
P-MP	Point-to-multipoint
PMR	Private mobile radio
POI	Probability of intercept
PoLA	Principle of least authority
PoMP	Principle of minimal privilege
PON	Passive optical network
P-P	point-to-point
PPP	Precise point positioning
PPS	Pulse-per-second
PRF	Pulse repetition frequency
PRI	Pulse repetition interval

PRN	Pseudo random number
PRT	Pulse repetition time
PSD	Power-spectral density
PSK	Phase shift keying
PSTN	Public switched telephone network
QAM	Quadrature amplitude modulation
QoS	Quality of service
QP	Quasi-peak (referring to the quasi-peak-detector)
QPSK	Quadrature phase shift keying
R.M.S. / r.m.s. / RMS / rms	Root mean square
r.p.m.	rotations per minute
RAG	Retrieval-augmented generation (not to be confused with the Radiocommunication Advisory Group)
RAN	Radio access network
RB	Resource block
RBAC	Role-based access control
RBW	Resolution bandwidth
RDBS	Radio broadcast data system
RDF	Resource description framework
RDP	Remote desktop protocol
RDS	Radio data system
ReAct	Reason-and-act
RefBW	Reference bandwidth
REST/RESTfull	Representational state transfer
RF	Radio frequency
RL	Reinforcement learning
RLAN	Radio local area network
RNC	Radio network controller
RNN	Recurrent neural network
RNSS	Radio navigation satellite service
RO	Reference oscillator
RR	ITU Radio Regulations
RRC (Chapter 3)	Radio resource control
RRC (Chapter 5)	Root raised cosine
RSSI	Received signal strength indication
RTP/RTCP	Real-time transport protocol
RTSA	Real-time spectrum analyser
RTWP	Received total wide band power
S/N	Signal-to-noise ratio
S+N/N	Signal-plus-noise to noise ratio
SaaS	Software as a service
SAR	Synthetic aperture radar
SCA	Subsidiary Communication Authority
SC-FDMA	Single carrier frequency division multiple access
SCN	Single carrier noise

SCPC	Single channel per carrier
SCPI	Standard commands for programmable instruments
SCTP	Stream control transmission protocol
SDK	Software development kit
SDMA	Spatial division multiple access
SDR	Software defined radio
SFN	Single frequency networks
SFTP	Secure file transfer protocol
SG	Study Group
SHF	Super high frequency band (3 to 30 GHz), see RR No. **2.1**
SINAD	Signal in noise and distortion
SINR	Signal to interference plus noise ratio
SIR	Signal to interference ratio
SNMP	Simple network management protocol
SNR	Signal-to-noise ratio
SOI	Signal-of-interest
SPOF	Single point of failure
SRAM	Static random access memory
SRO	Spectrum resource occupancy
SSB (Chapter 6.3)	Synchronization and signalling block
SSB (Chapters 3, 5 and 7)	Single/suppressed side band
SSD	Solid state drive
SSH	Secure shell
SSL	Single site location
SUV	Sport utility vehicle
SVM	Support vector machine
TCA	Time of closest approach
TCP/IP	Transmission control protocol/internet protocol
T-DAB	Terrestrial digital audio broadcasting
TDD	Time division duplex
TDM	Time-division-multiplex
TDMA	Time division multiple access
T-DMB	Terrestrial digital media broadcasting
TDOA	Time difference of arrival
TDR	Time domain reflectometer
TEC	Technical Evaluation Committee
TEP	Total evaluated price
TETRA	Terrestrial trunked radio
THD	Total harmonic distortion
TIA	Telecommunications Industry Association
TLE	Two-line elements
TR69	Technical Report 069 from Broadband Forum
TRP	Total radiated power
TV	Television
UDP	User datagram protocol

UE	User equipment
UHF	Ultra high frequency band (300 to 3 000 MHz), see RR No. **2.1**
UI	User interface
UMTS	Universal mobile telecommunication system
UMTS (Chapter 5.6)	Universal mobile telecommunications service
UPS	Uninterruptible power supply
USB	Upper side band
USBTMC	USB test & measurement class
USD	US Dollar
UTM	Universal transverse mercator
UX	User experience
VBW	Video bandwidth
VHF	Very high frequency band (30 to 300 MHz), see RR No. **2.1**
VISA	Virtual instrument software architecture
VITA	VMEbus international trade association
VLF	Very low frequency band (3 to 30 kHz), see RR No. **2.1**
VNA	Vector network analyser
VOR	VHF omnidirectional range
VPN	Virtual private network
VRT	VITA radio transport
VSA	Vector signal analyser
VSAT	Very small aperture terminal
VSB	Vestigal sideband
VSWR	Voltage standing wave ratio
WAN	Wide area network
WB	World Bank
WCDMA	Wideband code division multiple access
WebRTC	Web real-time communication
WFM	Wideband frequency modulation
WGN	White Gaussian noise
WHO	World Health Organization
WiFi	Wireless Fidelity (a WLAN operated according to IEEE 802.11)
WLAN	Wireless LAN
WPT	Wireless power transfer
WRC	World Radiocommunication Conference
WTDC	World Telecommunication Development Conference
WW	Watson-Watt
YIG	Yttrium Iron Garnet (crystalline material)

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