Handbook on
Use of Radio Spectrum for Meteorology: Weather, Water and Climate Monitoring and Prediction

Edition of 2017

WMO

ITU

HANDBOOK

Use of Radio Spectrum for Meteorology:
Weather, Water and Climate Monitoring and Prediction

Edition of 2017

Radiocommunication Bureau

PREFACE

"*Climate change is a direct threat in itself and a multiplier of many other threats — from poverty to displacement to conflict***"**

António Guterres, UN Secretary-General

WMO - World Meteorological Congress (Geneva, 2015), in Resolution 29 (Cg-17):

Considering:

(1) The prime importance of the specific radiocommunication services for meteorological and

related environmental activities required for the detection and early warning of hazards and the prevention and mitigation of natural and technological (human-induced) disasters, the safety of life and property, the protection of the environment, climate change studies and scientific research,

...

Stressing that some radio-frequency bands are a unique natural resource due to their special characteristics and natural radiation enabling space-borne passive sensing of the atmosphere and the Earth surface, which deserve adequate allocation to the Earth-exploration satellite service (passive) and absolute protection from interference,

…

Urges all Membersto do their utmost to ensure the availability and protection of suitable radiofrequency bands

…

Appeals to the International Telecommunication Union and its Member Administrations:

(1) To ensure the availability and absolute protection of the radio-frequency bands which, due to their special physical characteristics, are a unique natural resource for spaceborne passive sensing of the atmosphere and the Earth surface and are of crucial importance for weather, water and climate research and operations;

(2) To give due consideration to the WMO requirements for radio-frequency allocations and regulatory provisions for meteorological and related environmental operations and research;

…

ITU World Radiocommunication Conference (Geneva, 2012), in Resolution 673 (WRC-12):

"considering

...

b) that Earth observation data are also essential for monitoring and predicting climate changes, for disaster prediction, monitoring and mitigation, for increasing the understanding, modelling and verification of all aspects of climate change, and for related policy-making;

...

e) that many observations are performed over the entire world which require spectrum-related issues to be considered on a worldwide basis;

...

h) that Earth observations are performed for the benefit of the whole international community and the data are generally made available at no cost,

…

resolves

1   to continue to recognize that the use of spectrum by Earth observation applications has a considerable societal and economic value;

2   to urge administrations to take into account Earth observation radio-frequency requirements and in particular protection of the Earth observation systems in the related frequency bands;

3   to encourage administrations to consider the importance of the use and availability of spectrum for Earth observation applications prior to taking decisions that would negatively impact the operation of these applications."

Between 1970 and 2015, more than 12 000 natural disasters worldwide took the lives of over 3.5 million people and produced economic losses estimated at over 2.7 trillion US dollars. Ninety per cent of these natural disasters, more than 60% of casualties and 70% of economic losses were caused by weather-, climate- and water-related hazards, such as droughts, floods, severe storms and tropical cyclones as well as by health epidemics and insect infestations directly linked to meteorological and hydrological conditions. These extreme events are intensifying with climate change, the "defining challenge of our time", and will continue to do so if it is left unaddressed. There is indeed overwhelming scientific evidence that climate change will threaten economic growth, long term prosperity and social welfare of practically all countries, as well as the very survival of the most vulnerable populations.

In understanding and addressing climate change and its impacts, observation and monitoring technologies and infrastructure play a critical role. At present, radio-based applications such as remote sensing instruments operating on-board satellites and on the earth surface (e.g. weather radars) provide the main source of information about the Earth's atmosphere and surface. In turn, this information is used for climate, weather and water monitoring, prediction and warnings, natural disasters risk reduction, support of disaster-relief operations and for planning preventive measures for adapting to and mitigating the negative effects of climate change.

Areas foreseen in this context include: continued observations and long-term monitoring of solar activity to improve our knowledge and understanding of the influence of the electromagnetic radiation from the sun on Earth's environment, including climate; continued observations to characterize changes in the atmosphere, oceans, land surface, and the cryosphere, and the use of such information for climate change modelling; and continued observations of the change in the ozone layer and its effects on the environment and human health. Land cover change assessment and understanding of its dynamics are recognized as essential requirements for sustainable management of natural resources, environmental protection, food security, climate change and humanitarian programmes. Terrestrial and satellite radiocommunication systems contribute to the monitoring of carbon emissions, the changing of ice in polar caps and glaciers, and temperature changes.

For more than 140 years, starting with the International Telegraph Union and the International Meteorological Organization in the late 1800s, to respectively become the International Telecommunication Union (ITU) and the World Meteorological Organization (WMO) in the 1950s, there has been fruitful collaboration and partnership between the global meteorological and telecommunication agencies. Whilst WMO focuses its efforts on meeting the needs for environmental information and the corresponding radio frequency spectrum for standardized weather, climate and hydrological applications, ITU, as international steward of the radio spectrum, allocates the necessary radio frequencies to allow the interference-free operation of radio-based applications and radiocommunication systems (terrestrial and space) used for climate monitoring and prediction, weather forecasting and disaster early warning and detection.
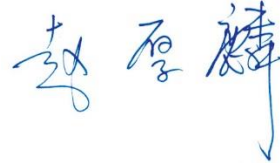
Successive ITU World Radiocommunication Conferences have taken into account the needs of WMO to ensure the availability and protection of radio-frequency bands for such atmospheric and other environmental observation tools as radiosondes, weather and wind profiler radars and spaceborne infrared and microwave sounders.

This new version of the Handbook on Use of Radio Spectrum for Meteorology: Weather, Water and Climate Monitoring and Prediction has been jointly developed by experts of ITU-R Working Party 7C under the chairmanship of Mr. M. Dreis (EUMETSAT) of ITU-R Radiocommunication Study Group 7 (Science Services), and the Steering Group on Radio Frequency Coordination (SG-RFC) of the WMO Commission for Basic Systems (CBS), under the chairmanship of Mr. Eric Allaix (France).

The Handbook provides comprehensive technical and operational information on current observation applications and systems and on the use of radio frequencies by meteorological systems, including meteorological satellites, radiosondes, weather radars, wind profiler radars and spaceborne remote sensing instruments. It is intended for the meteorological (i.e. weather, water and climate) and radiocommunication communities, including governmental institutions, industry as well as the general public.

Mr. Petteri Taalas
Secretary-General
World Meteorological Organization

Mr. Houlin Zhao
Secretary-General
International Telecommunication Union

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FOREWORD

The Radiocommunication Study Group 7 for the Science Services was created through a structural reorganization in 1990 at the Düsseldorf CCIR Plenary Assembly.

Study Group 7 comprises a number of Radiocommunication Working Parties (WP) that addresses technical issues related to specific disciplines under the umbrella of science services. Meteorology and related environmental activities fall within the remit of Working Party 7C (WP 7C). WP 7C carries out studies concerning the implementation and operation of meteorological passive and active sensors, from both ground-based and space-based platforms, as well as meteorological aids (mainly radiosondes). As meteorology also depends on radio both to collect the data upon which its predictions are based, and to process and disseminate weather information and warnings to the public, this activity concerns WP 7B. Finally, one can note that meteorological radars and wind-profiler radars are studied within WP 5B, under the general radiolocation service.

Meteorology is a crucial part of our everyday life and has many connections with our daily routines and activities. Weather forecasts are among the most popular programmes on TV or radio today. Not only does the weather forecast affect the way we dress or decide what to do each day, it also has many implications on public safety. Public transportation is highly dependent on weather forecasting. The ability to accurately predict weather is essential to provide a high level of services to society, including in particular protection of life and properties in many areas such as transportation, especially for aviation. In this period of great meteorological and climate disturbances, this activity also plays a major role in the prediction, detection and mitigation of the negative effects of natural disasters.

The development of Recommendations and the preparation for the World Radiocommunication Conferences (WRC) is the principal focus of the Study Group activities. There is an unmistakable need for the Study Group 7 experts to share this information not only with their colleagues whose work depends on meteorological data for improving the accuracy of weather and climate prediction, but also with a more general audience in order for the interested person to understand the importance of using specific frequencies for meteorological purposes and the ways to protect them so as to continue meteorological forecasting with the highest possible degree of reliability.

Thus it was decided to prepare and publish this Handbook, in collaboration with the Steering Group on Radio Frequency Coordination (SG-RFC) of the World Meteorological Organization (WMO), so that all users of these standards could more completely understand meteorological systems in order to better design and apply these powerful tools. One primary purpose of this Handbook is to provide the reader with information about the use of radio systems and radio frequency (RF) bands by meteorologists and other scientists interested in environmental activities worldwide, and the importance of this use to public safety and the world economy.

Effective and prudent management of allocated frequency bands is paramount to maintaining and enhancing the quality and accuracy of weather and weather-related predictions. It is essential to understand for instance that if some the frequency bands currently allocated for meteorological purposes were to be used by other radio systems that are incompatible with meteorological radio systems, then these bands could be rendered unusable for weather, climate and/or disaster prediction systems, thus make corresponding weather forecasts extremely difficult if not impossible with the required degree of reliability and accuracy.

As Chairman of Study Group 7, it is my great pleasure to present this Handbook to the community of users of meteorological standards, and to the frequency management community at large who will, I am sure, find it an important reference tool in their own work.

This Handbook could not have been completed without the contributions from many administrations participating in Study Group 7 and SG-RFC. Moreover, the work of the Rapporteurs for the various sections of the Handbook was outstanding and special thanks should be given to Mr. David Franc (USA), Mr. Gilles Fournier (Canada), Mr. Eric Allaix (France), Mr. David Thomas (WMO), Mr. Philippe Tristant (EUMETNET) and Mr. Markus Dreis (EUMETSAT) for their leadership of this project.

Our special gratitude is also due to Mr. Vadim Nozdrin of the Radiocommunication Bureau who has played an important role in the publication of the Handbook.

John Zuzek
Chairman, Radiocommunication Study Group 7

INTRODUCTION

Timely warning of natural and environmental disasters, accurate climate prediction and a detailed understanding, conservation and efficient management of scarce resources such as biomass, biosphere, mineral resources, water, and energy are essential requirements for sustainable economic development. Information about climate, climate change, weather, cryosphere, precipitation, pollution or disasters is a critically important everyday issue for the global community. Monitoring activities provide this information, which is required for the daily weather forecast and prediction, studies of climate change, for the protection of the environment, for economic development (transport, energy, agriculture, building construction, urban development, deployment of utilities, agriculture, security) and for safety of life and property. Earth observations are also used to obtain pertinent data regarding natural resources, this being particularly crucial for developing countries. It is important not to forget that this information is either based on measurements from, or gathered, provided and distributed by radiocommunication systems. Radio systems are fundamental to monitoring the climate and helping countries to mitigate and adapt to the effects of climate change and in addressing its major challenges. Any radio system that uses radio spectrum for its operation uses a limited, scarce resource. Availability of radio frequency bands free from harmful interference is a requirement for the development of all Earth observation systems.

The systems used to obtain and disseminate this information require reliable access to radio frequencies ranging from few kHz to several hundred of GHz and make use of a variety of radio technologies such as radiocommunication (e.g. for radiosondes or satellites), weather radars (precipitation and wind profilers, as well as active sensors used in space) and space-based, surface-based and radio-based detection (e.g. passive satellite remote sensing or lightning detection).

It should be understood that these radio-frequency applications are inter-related and help to comprise a global meteorological system, and that the lack of any of this system's radio components, whether related to observation or to data dissemination, can put the whole meteorological process at risk.

It is also emphasised that systems using these frequencies have a crucial role in detecting, warning and forecasting weather, water and climate related disasters. Since these disasters represent more than 90% of natural disasters, these systems are essential components of all-hazards emergency and disasters early-warning and mitigation systems.

The development of new, mass-market and added-value radio applications is putting increasing pressure on the frequency bands used for meteorological purposes. It presents the potential risk of limiting meteorological applications in future. At particular risk is satellite passive remote sensing which involves the measurement of very low levels of naturally emitted radiation in a number of radio frequency bands. These bands are sensitive to more than one geophysical variable and therefore must be used together to derive a number of different quantities. The radio frequencies required to do this are determined by fundamental physics and are unalterable. Continuity of observations using these bands is also essential to the monitoring and assessment of climate change.

Meteorological users of the spectrum must remain vigilant and increasingly address issues concerning sharing of the spectrum with other radiocommunication services. In recognition of the prime importance of the specific radiocommunication services for meteorological and related environmental activities required for the safety of life and property, the protection of the environment, climate change studies and scientific research, the World Meteorological Organisation (WMO) Resolution 29 (Cg-17) appeals to the International Telecommunication Union (ITU) and its Member Administrations:

−   to ensure the availability and absolute protection of the radio-frequency bands which, due to their special physical characteristics, are a unique natural resource for spaceborne passive sensing of the atmosphere and the Earth surface and are of crucial importance for weather, water and climate research and operations;

−   to give due consideration to the WMO requirements for radio frequency allocations and regulatory provisions for meteorological and related environmental operations and research.

In this respect, the last World Radiocommunications Conferences (WRC) made a number of important decisions in relation to safeguarding meteorological and related environmental operations. This was in particular the case at WRC-15 that provided additional spectrum for the future development of space active remote sensing and high date rate telecommand links to communicate with Earth exploration satellites, as well as protection to passive observation bands potentially impacted by new allocations. Taking into account growing demand for spectrum use from commercial services, WRC-19 and WRC-23 will be very important for meteorological community in order to protect their spectrum and future worldwide development of modern observation systems.

In an attempt to placing these studies in perspective, Radiocommunication Working Party 7C (Remote Sensing Systems) of Radiocommunication Study Group 7 and the WMO Steering Group on Radio Frequency Coordination (SG-RFC) have prepared this revised Handbook that is intended to serve as a guide to the professional users of radio-based meteorological systems data; to the people and governments served by these meteorological systems and to the radiocommunications community, including regulators and wireless telecommunications industry.

This Handbook provides an overview of the use of radiocommunication systems to monitor the various manifestations of climate change and their impact as well as the application of ICTs and radiocommunication as a solution to contribute to a global reduction in energy consumption.

This Handbook presents meteorological systems as well as an overview and discussion of each system's technical and operational characteristics. The description of each meteorological system includes: the RF bands employed; the criteria by which harmful interference from competing users may be predicted; and the impact of weather data degradation or loss on public safety. To assist in understanding this complex area, discussions have been divided into the following types of system:

1   General structure of meteorological systems

2   Meteorological satellite service systems

3   Meteorological aids service systems, mainly radiosondes

4   Ground-based meteorological radars, including weather radars and wind-profiler radars

5   Passive and active spaceborne remote sensing for meteorological activities

6   Other radiocommunication systems for meteorological activities

To aid the reader, a brief compendium of acronyms and abbreviations is attached along with a pointer to a more complete set of definitions of meteorological terminology.

<div align="center">

CHAPTER 1

GENERAL STRUCTURE OF METEOROLOGICAL SYSTEMS

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1.1   Meteorological systems of the World Weather Watch

To analyse, warn and predict the weather, modern meteorology depends upon near instantaneous exchange of weather information across the entire globe. The World Weather Watch (WWW), the core of the WMO Programmes, combines observing systems, telecommunication facilities, and data-processing and forecasting centres – operated by the 191 Member States and Territories – to make available meteorological and related geophysical information needed to provide efficient services in all countries.

The World Weather Watch is coordinated and monitored by WMO with a view to ensuring that every country has available all of the information it needs to provide weather services (analysis, warnings and predictions) on a day-to-day basis as well as for long-term planning and research. An increasingly important part of the WWW Programme provides support for international programmes related to global climate, especially climate change as well as other environmental issues, and to sustainable development.

The World Weather Watch (WWW) is composed of three integrated core system components (see Fig. 1-1):

–   The **Global Observing System (GOS)** provides high-quality, standardized observations of the atmosphere and ocean surface from all parts of the globe and from outer space. The GOS is a major component of the WMO global integrated observing system (WIGOS) described briefly below.

–   The **Global Telecommunication System (GTS)** provides for the real-time exchange of meteorological observational data, processed products, and related information between national meteorological and hydrological services. The GTS is a major component of the WMO information system (WIS) utilizing dedicated terrestrial and space based networks, including radio and video broadcast technologies. WIS also makes extensive use of the Internet.

–   The **Global Data Processing and Forecasting System** provides processed meteorological products (analysis, warnings, and forecasts) that are generated by a network of World Meteorological Centres and specialized Regional Meteorological Centres.

FIGURE 1-1

World Weather Watch systems

Meteo-01-01

1.1.1 Global Observing System

The Global Observing System (GOS) is the primary source of technical information on the world's atmosphere, and is a composite system of complex methods, techniques and facilities for measuring meteorological and environmental parameters. GOS ensures that critical information is available to every country to generate weather analyses, forecasts and warnings on a day-to-day basis. As shown in Fig. 1-2, GOS is comprised of observing stations located on land, at sea, on aircraft, and on meteorological satellites.

The most obvious benefits of GOS are the safeguarding of life and property through the detection, forecasting, and warning of severe weather phenomena such as local storms, tornadoes, hurricanes, or extra-tropical and tropical cyclones. GOS provides in particular observational data for agrometeorology, aeronautical meteorology and climatology, including the study of climate and global change. Data from GOS are also used in support of environmental programs everywhere.

A wide range of economic activities such as farming, transportation, construction, public weather services and tourism benefits enormously from weather forecasts that extend from a few days to weeks, or even seasons.

Detailed information on GOS is available at: http://www.wmo.int/pages/prog/sat/satellitestatus.php .

FIGURE 1-2

WMO Global Observing System GOS
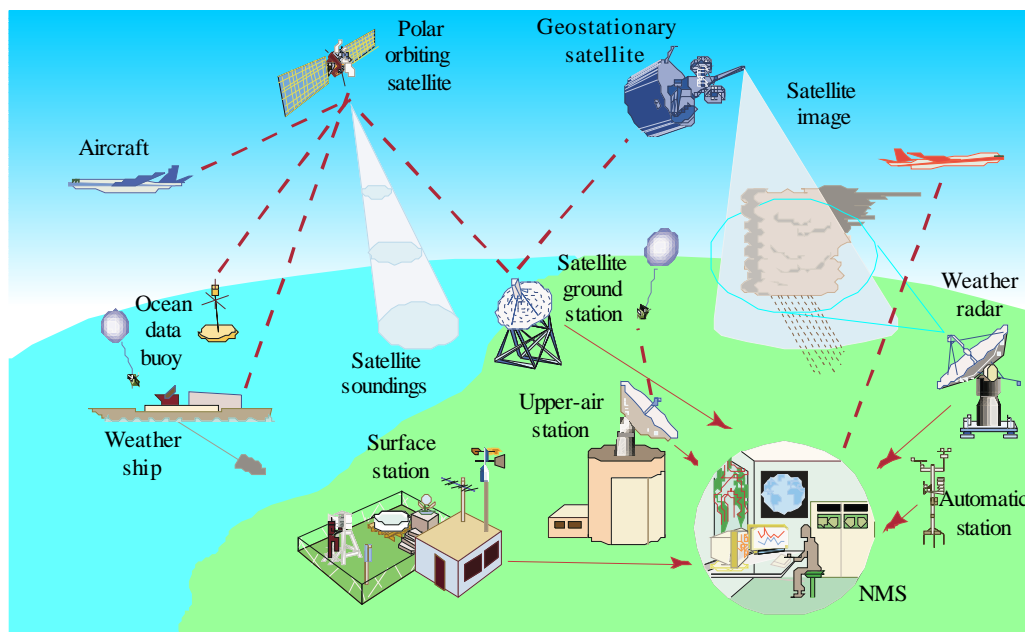
Meteo-01-02

1.1.1.1 Surface observing

The backbone of the surface-based system continues to be approximately 10 000 stations on land making observations at or near the Earth's surface. Observations are made of meteorological parameters such as atmospheric pressure, wind speed and direction, air temperature, and relative humidity every one to three hours. Data from these stations are exchanged globally in real time. A subset of observed data from these surface stations, the Global Climate Observing System (GCOS) Surface Network, is also used for climate monitoring purposes in the GCOS.

1.1.1.2 Upper-air observing

From a network of roughly 900 upper-air stations around the world representing about 800 000 yearly lunches, radiosondes attached to free-rising balloons take measurements of pressure, wind velocity, temperature, and humidity from just above ground to heights up to 30 km. In ocean areas, radiosonde observations are taken by

about 20 ships, which mainly ply the North Atlantic, fitted with automated shipboard upper-air sounding facilities. A subset of upper-air stations, specially fitted for monitoring the climate, comprises the GCOS Upper-air Network.

1.1.1.3 Radar observations

Weather and wind-profiling radars are proving to be extremely valuable in providing data of high-resolution in both space and time, especially in the lower layers of the atmosphere. Weather radars are used extensively as part of national, and increasingly of regional networks, mainly for short-range forecasting of severe weather phenomena. Weather radars are particularly useful for estimation of rainfall amounts and, when Doppler capable, wind measurements. Wind profiler radars are especially useful in making observations between balloon-borne soundings, and have great potential as a part of integrated observing networks.

1.1.1.4 Observing stations at sea

Over the oceans, the GOS relies on ships, moored and drifting buoys, and stationary platforms. Observations made by about 7 000 ships recruited under the WMO Voluntary Observing Ship Programme, collect the same variables as land stations with the important additions of sea surface temperature and wave height and period. The operational drifting buoy programme comprises about 900 drifting buoys providing 12 000 sea surface temperature and surface air pressure reports per day.

In addition, Tsunami Warning Systems, owned and operated by Member States, have been established under the aegis of the IOC of UNESCO, in cooperation with the WMO in the Pacific and Indian oceans, and are planned in other maritime areas; they include a network of real-time surface and deep-sea level sensors for the detection, early warning and monitoring of tsunamis.

1.1.1.5 Observations from aircraft

Over 4 000 aircraft provide reports of pressure, winds, and temperature during flight. The Aircraft Meteorological Data Relay (AMDAR) system makes high-quality observations of winds and temperature at cruising level, as well as at selected levels in ascent and descent. The amount of data from aircraft has increased dramatically in recent years to an estimated 700 000 reports per day corresponding to approximately 90 000 profiles of AMDAR data at 550 airports globally. These systems provide great potential for measurements in places where there are little or no radiosonde data, and make a major contribution to the upper-air component of the GOS.

1.1.1.6 Observations from satellites

The environmental and meteorological space-based Global Observing System includes constellations of operational geostationary and non-geostationary (mostly polar orbiting and at low altitude) observation satellites. An overview of the currently operational meteorological satellites (Status: June 2016) is shown in Fig. 1-3.

Polar orbiting and geostationary satellites are normally equipped with visible and infrared imagers and sounders, from which one can derive many meteorological parameters. Several of the polar-orbiting satellites are equipped with microwave sounding instruments that can provide vertical profiles of temperature and humidity worldwide. Geostationary satellites can be used to measure wind velocity in the tropics by tracking clouds and water vapour. Satellite sensors, communications, and data assimilation techniques are evolving steadily, and the vast amount of additional satellite data has greatly improved weather and climate monitoring, warning and forecasting.

Improvements in numerical modelling in particular have made it possible to develop increasingly sophisticated methods of deriving temperature and humidity information directly from the satellite radiances. The impressive progress made in the recent years in weather and climate analysis and forecasts, including warnings for dangerous weather phenomena (heavy rain, storms, cyclones) that affect all populations and economies, is to a great extent attributable to space-borne observations and their assimilation in numerical models.

FIGURE 1-3

Constellation of the currently operational meteorological satellites of the WMO GOS (Status: June 2016)

Currently operational meteorological satellites (status: June 2016, information source: CGMS)

Geostationary meteorological satellites

1. GOES-15 (USA) 135°W
2. GOES-14 (USA) 135°W (stand-by)
3. GOES-13 (USA) 75°W
4. METEOSAT-11 (EUMETSAT) 3.4°W (stand-by)
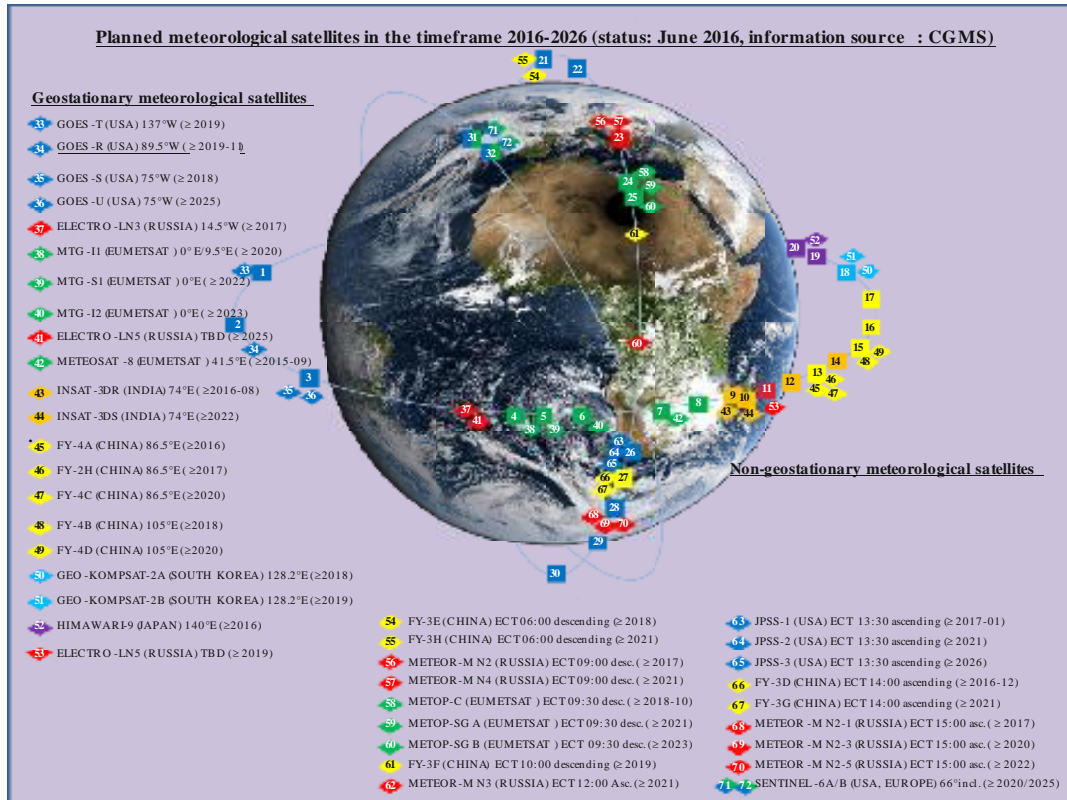5. METEOSAT-10 (EUMETSAT) 0°
6. METEOSAT-9 (EUMETSAT) 9.5°E
7. METEOSAT-8 (EUMETSAT) 41.5°E
8. METEOSAT-7 (EUMETSAT) 57.5°E
9. INSAT-3 (INDIA) 74°E
10. KALPANA-1 (INDIA) 74°E
11. ELECTRO-LN 2 (RUSSIA) 77.8°E
12. INSAT-3C (INDIA) 82°E
13. FY-2E (CHINA) 86.5°E
14. INSAT-3A (INDIA) 93.5°E
15. FY-2G (CHINA) 105°E
16. FY-2F (CHINA) 112.5°E (stand-by)
17. FY-2D (CHINA) 123.5°E
18. COMS-1 (SOUTH KOREA) 128.2°E
19. HIMAWARI-8 (JAPAN) 140.7°E
20. HIMAWARI-7 (JAPAN) 145°E (stand-by)

Non-geostationary meteorological satellites

21. DMPS-F17 (USA) ECT 06:20 descending
22. DMPS-F17 (USA) ECT 07:08 descending
23. METEOR-M N2 (RUSSIA) ECT 09:10 descending
24. METOP-A (EUMETSAT) ECT 09:30 descending
25. METOP-B (EUMETSAT) ECT 09:30 descending
26. SNPP (USA) ECT 13:29 ascending
27. FY-3B (CHINA) ECT 13:38 ascending
28. NOAA-19 (USA) ECT 14:36 ascending
29. DMSP-F16 (USA) ECT 16:12 ascending
30. NOAA-18 (USA) ECT 17:53 ascending
31. JASON-2 (USA, EUROPE) 66° inclination
32. JASON-3 (USA, EUROPE) 66° inclination

Meteo-01-03

A list of current operational meteorological satellites and their parameters is available at: http://www.wmo.int/pages/prog/sat/satellitestatus.php .

In order to provide operational continuity in the space-based meteorological observations the currently operational satellites will be replaced by new satellites of the existing series of its generation of meteorological satellites or first satellites of the next generation meteorological satellites, having increased observation capabilities and resolution of the instruments resulting in significantly higher data volume available to the meteorological user community.

Figure 1-4 provides an overview of the planned launches of meteorological satellites to become operational in the timeframe 2016-2026 in addition to the currently operational satellites. Newly launched satellites will be operated in parallel with aging satellites until they will be gradually phased-out when reaching end of life.

FIGURE 1-4

Constellation of planned meteorological satellites of the WMO GOS to become operational in the timeframe 2016-2026 (Status: June 2016)

Planned meteorological satellites in the timeframe 2016-2026 (status: June 2016, information source : CGMS)

Geostationary meteorological satellites

33 GOES -T (USA) 137°W (≥ 2019)
34 GOES -R (USA) 89.5°W (≥ 2019-1I)
35 GOES -S (USA) 75°W (≥ 2018)
36 GOES -U (USA) 75°W (≥ 2025)
37 ELECTRO -LN3 (RUSSIA) 14.5°W (≥ 2017)
38 MTG -I1 (EUMETSAT) 0°E/9.5°E (≥ 2020)
39 MTG -S1 (EUMETSAT) 0°E (≥ 2022)
40 MTG -I2 (EUMETSAT) 0°E (≥ 2023)
41 ELECTRO -LN5 (RUSSIA) TBD (≥ 2025)
42 METEOSAT -8 (EUMETSAT) 41.5°E (≥2015-09)
43 INSAT -3DR (INDIA) 74°E (≥2016-08)
44 INSAT -3DS (INDIA) 74°E (≥2022)
45 FY-4A (CHINA) 86.5°E (≥2016)
46 FY-2H (CHINA) 86.5°E (≥2017)
47 FY-4C (CHINA) 86.5°E (≥2020)
48 FY-4B (CHINA) 105°E (≥2018)
49 FY-4D (CHINA) 105°E (≥2020)
50 GEO -KOMPSAT-2A (SOUTH KOREA) 128.2°E (≥2018)
51 GEO -KOMPSAT-2B (SOUTH KOREA) 128.2°E (≥2019)
52 HIMAWARI-9 (JAPAN) 140°E (≥2016)
53 ELECTRO -LN5 (RUSSIA) TBD (≥ 2019)

Non-geostationary meteorological satellites

54 FY-3E (CHINA) ECT 06:00 descending (≥ 2018)
55 FY-3H (CHINA) ECT 06:00 descending (≥ 2021)
56 METEOR-M N2 (RUSSIA) ECT 09:00 desc.(≥ 2017)
57 METEOR-M N4 (RUSSIA) ECT 09:00 desc.(≥ 2021)
58 METOP-C (EUMETSAT) ECT 09:30 desc.(≥ 2018-10)
59 METOP-SG A (EUMETSAT) ECT 09:30 desc.(≥ 2021)
60 METOP-SG B (EUMETSAT) ECT 09:30 desc.(≥ 2023)
61 FY-3F (CHINA) ECT 10:00 descending (≥ 2019)
62 METEOR-M N3 (RUSSIA) ECT 12:00 Asc.(≥ 2021)
63 JPSS-1 (USA) ECT 13:30 ascending (≥ 2017-01)
64 JPSS-2 (USA) ECT 13:30 ascending (≥ 2021)
65 JPSS-3 (USA) ECT 13:30 ascending (≥ 2026)
66 FY-3D (CHINA) ECT 14:00 ascending (≥ 2016-12)
67 FY-3G (CHINA) ECT 14:00 ascending (≥ 2021)
68 METEOR -M N2-1 (RUSSIA) ECT 15:00 asc.(≥ 2017)
69 METEOR -M N2-3 (RUSSIA) ECT 15:00 asc.(≥ 2020)
70 METEOR -M N2-5 (RUSSIA) ECT 15:00 asc.(≥ 2022)
71 72 SENTINEL -6A/B (USA, EUROPE) 66°incl. (≥ 2020/2025)

Meteo-01-04

In addition, a number of Research and Development (R&D) satellites also include specific meteorological or climatological payload that are also contributing to the GOS. A list of current R&D satellites and their parameters is available at: http://www.wmo.int/pages/prog/sat/GOSresearch.html .

Research and Development satellites comprise the newest constellation in the space-based component of the GOS. R&D missions provide valuable data for operational use as well as for many WMO supported programmes. Instruments on R&D missions either provide data not normally observed from operational meteorological satellites or improvements to current operational systems.

1.2 Observing systems of other WMO programmes

1.2.1 WMO Global Atmosphere Watch

The WMO Global Atmosphere Watch (GAW) integrates a number of WMO research and monitoring activities in the field of the atmospheric environment including the WMO Background Air Pollution Monitoring Network and the WMO Global Ozone Observing System. It includes more than 20 observatories and over 300 regional stations. The main objective of GAW is to provide information on the chemical composition and related physical characteristics of the atmosphere needed to improve understanding of the behaviour of the atmosphere and its interactions with the oceans and the biosphere. Other GAW observing systems provide solar radiation observations, lightning detection, and tide-gauge measurements. GAW is the atmospheric chemistry component of the Global Climate Observing System.

1.2.2 Global Climate Observing System

The Global Climate Observing System (GCOS) is intended to provide the comprehensive observations required for monitoring the climate system, for detecting and attributing climate change, for assessing the impacts of climate variability and change, and for supporting research toward improved understanding, modelling and prediction of the climate system, especially climate change. GCOS addresses the total climate system including physical, chemical and biological properties, and atmospheric, oceanic, hydrologic, cryospheric and terrestrial processes.

1.2.3 Hydrology and water resources programme

This programme provides for the measurement of basic hydrological elements from networks of hydrological and meteorological stations. These stations collect, process, store, and utilize hydrological data, including data on the quantity and quality of both surface water and groundwater. The programme includes the World Hydrological Cycle Observing System (WHYCOS), which is based on a global network of reference stations, and which transmit hydrological and meteorological data in near real-time.

1.3 WMO Integrated Global Observing Systems (WIGOS)

The Members of WMO, at their 2007 Congress, decided to work towards enhanced integration of WMO observing systems and of WMO supported observing systems such as the Global Ocean Observing System (GOOS), Global Terrestrial Observing System (GTOS) and GCOS. The WMO Integrated Global Observing Systems (WIGOS) concept is to provide a single focus for the operational and management functions of all WMO observing systems as well as a mechanism for interactions with WMO co-sponsored observing systems. Integration will lead to efficiencies and cost savings. WIGOS main objectives are:

– Increasing interoperability between systems with particular attention given to space-based and *in situ* components of the systems.

– Addressing the needs of the atmospheric, hydrologic, oceanographic, cryospheric and terrestrial domains within the operational scope of a comprehensive integrated system.

– Ensuring broader governance frameworks and improving WMO management and governance.

CHAPTER 2

METEOROLOGICAL SATELLITE SERVICE (MetSat)

Page

2.1   Definition of the meteorological satellite service (MetSat) and its frequency allocations

The meteorological satellite service (MetSat) is defined in No. **1.52** of the Radio Regulations (RR) as "an *earth exploration-satellite service* for meteorological purposes". It allows the radiocommunication operation between earth stations and one or more space stations, which may include links between space stations, with links to provide:

–   information relating to the characteristics of the Earth and its natural phenomena, including data relating to the state of the environment, obtained from active or passive sensors on Earth satellites;

–   information collected from airborne or Earth-based platforms;

–   information distributed to earth stations;

–   feeder links necessary for the operation of MetSat satellites and its applications.

This Chapter related to MetSat applications includes the following radiocommunication transmissions:

–   transmissions of observation data from MetSat satellites to main reception stations;

–   re-transmissions of pre-processed data to meteorological user stations through MetSat satellites;

–   direct broadcast transmissions to meteorological user stations from MetSat satellites;

–   alternative data dissemination to users (GEONETCast) via other satellite systems than MetSat;

–   transmissions from data collection platforms to MetSat satellites.

Table 2-1 indicates the frequency bands that are allocated in the ITU Radio Regulations to the meteorological satellite (MetSat) service and the Earth exploration-satellite service (EESS). MetSat systems are entitled to also use the frequency bands allocated to EESS for data transmissions (see Note 1).

TABLE 2-1

Frequency band allocations to MetSat and EESS in the ITU Radio Regulations for use by meteorological satellites for data transmissions

Available allocations for MetSat data transmissions	
space-to-Earth direction	**Earth-to-space direction**
137-138 MHz (MetSat primary)	**401-403 MHz** (EESS and MetSat primary)
400.15-401 MHz (MetSat primary)	**2 025-2 110 MHz** (EESS primary) (Note 1) (and space-to-space direction)
460-470 MHz (EESS and MetSat secondary[3])	**8 175-8 215 MHz** (MetSat primary)
1 670-1 710 MHz (MetSat primary)	**28.5-30.0 GHz** (EESS secondary) (Note 1)
2 200-2 290 MHz (EESS primary) (Note 1) (and space-to-space direction)	**40.0-40.5 GHz** (EESS primary) (Note 1)
7 450-7 550 MHz (MetSat primary, limited to geostationary satellites only)	
7 750-7 900 MHz (MetSat primary, limited to non-geostationary satellites only)	
8 025-8 400 MHz (EESS primary) (Note 1)	
18.0-18.3 GHz (MetSat primary for space-to-Earth direction in Region 2, limited to geostationary satellites only)	

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[3] By Footnote RR. 5.290, MetSat service is allocated on a primary basis in some countries.

TABLE 2-1 (*end*)

Available allocations for MetSat data transmissions	
18.1-18.4 GHz (MetSat primary for space-to-Earth direction in Regions 1 and 3, limited to geostationary satellites only)	
25.5-27.0 GHz (EESS primary) (Note 1) (and space-to-space direction in 25.25-27.5 GHz)	
37.5-40.0 GHz (EESS secondary) (Note 1)	
65.0-66.0 GHz (EESS primary) (Note 1)	

NOTE 1 − Since the MetSat is a sub-class of the Earth exploration-satellite service (EESS), those allocations (for example: 8 025-8 400 MHz and 25 500-27 000 MHz) can also be used for the operation of MetSat satellites and their applications.

2.1.1   General concept of MetSat satellite systems

MetSat system commonly collect a variety of data with visible and infrared imagers as well as with passive and active sensing instruments using also microwave frequencies allocated to that purpose (see Chapter 5).

The raw data gathered by the instruments on-board geostationary meteorological satellites are permanently transmitted to a primary ground station of the operating agency, processed, and distributed to various national meteorological centres, to official archives, and other users. Raw data, for example, include images of the Earth taken at several wavelengths so as to provide a variety of measurement data. Processed data are either sent back to the meteorological satellite for re-transmission as part of a direct broadcast to user stations via low and/or high rate digital signals or are directly distributed to users by using alternative means of data dissemination.

Different to geostationary MetSat satellites, where the satellite is permanently in visibility of its ground stations, the raw data acquired by the instruments on non-geostationary meteorological satellites have to be gathered and stored on-board the satellite until they can be transmitted to a primary ground station of the operating agency when the satellite passes over such a ground station. The raw instrument data are then processed by the operating agency and provided to the users by different data dissemination mechanisms. To improve the latency of the data, a subset of the data acquired by the instruments are "broadcasted" directly from the satellite and can be received by user stations when the satellite is in the visibility of such a user station which can be located anywhere. Such a service is called "direct read-out".
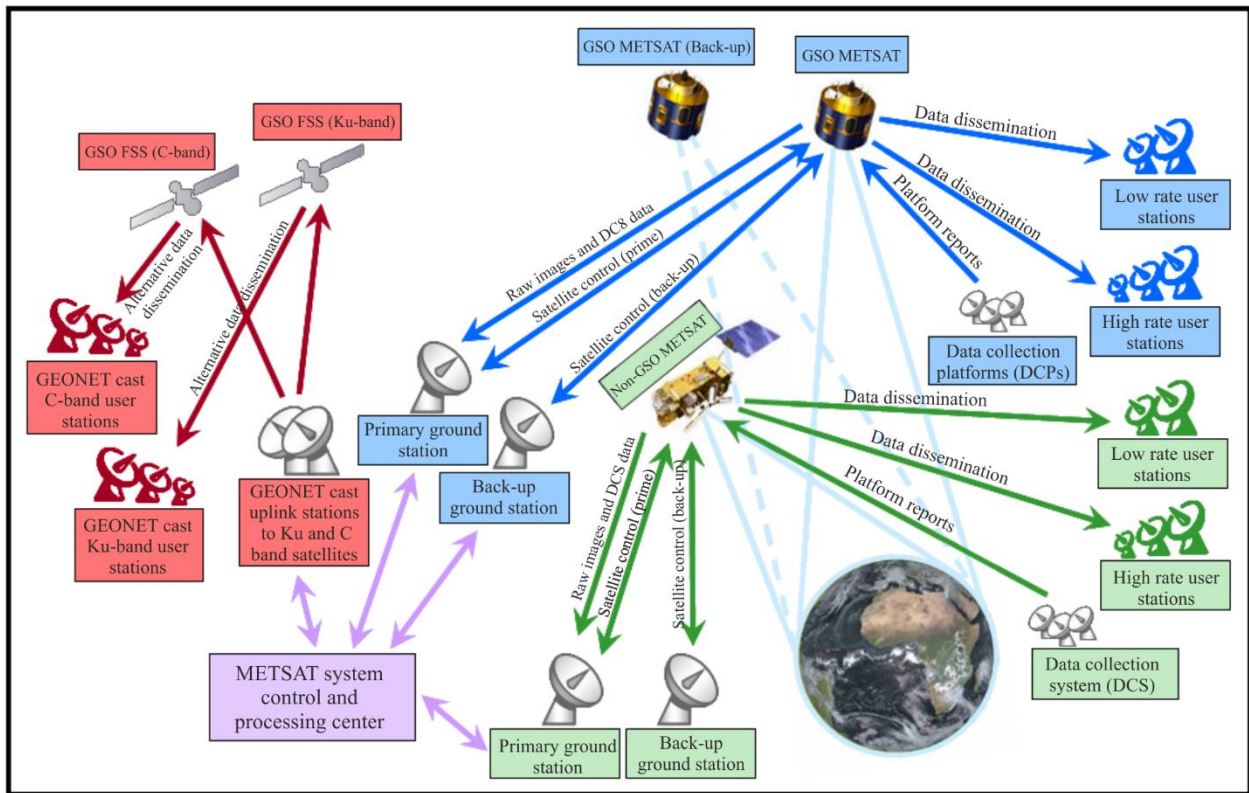
Meteorological satellites, geostationary and non-geostationary, also carry Data Collection Systems (DCS), namely Data Collection Platforms (DCPs) on geostationary orbit (GSO) satellites and systems such as Argos on non-geostationary orbit (non-GSO) satellites.

DCPs, typically located on ground, aircrafts, ships and floating buoys, transmit to geostationary meteorological satellites. The data collected by such DCPs are on parameters such as surface temperature, wind velocity, rainfall rate, stream height, gases in the atmosphere, and, in the case of floating buoys, oceanic pollutants. They may also transmit their current position, allowing movement to be determined. In addition to the operation of regional DCP channels, MetSat operators also contribute to the International Data Collection System (IDCS) through the operation of international channels. As an additional application, a dedicated number of IDCS channels can also be allocated for use by an emergency/disaster monitoring system.

Data collection platforms such as of the Argos system transmit to non-GSO MetSat satellites. When installed on buoys and floats, such platforms measure atmospheric pressure, wind speed and direction, sea surface currents and other sea parameters. Among other applications DCS systems on non-GSO satellites are also used to track animal movements as well as to monitor fishing fleets.

Figure 2-1 shows the general architecture of a MetSat system.

FIGURE 2-1

General architecture of a MetSat system

Meteo-02-01

## 2.2 MetSat systems using geostationary (GSO) satellites

In the framework of the Global Observing System of the World Weather Watch, a number of meteorological satellites are currently operated to ensure a full coverage observation of the Earth from the geostationary orbit (see Fig. 1-3). The continuous and long-term global coverage by observations from the geostationary orbit is ensured by scheduled future launches of meteorological satellites (see Fig. 1-4), replacing or further complementing existing satellite systems.

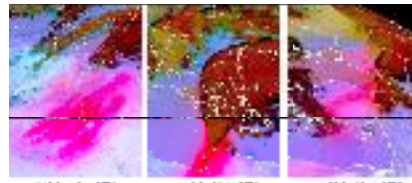### 2.2.1 GSO MetSat raw image sensor data transmissions

Data obtained by the visible, near-infrared and infrared imagers and other sensors on board GSO meteorological satellites are transmitted to main operations stations (often called Command and Data Acquisition, or CDA stations) in the 1 670-1 690 MHz band.

Figure 2-2 provides example images of processed data from the imager instrument on-board of a GSO meteorological satellite.
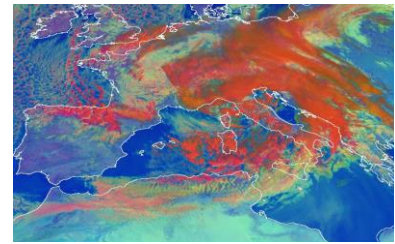
FIGURE 2-2

Image of processed data from a GSO meteorological satellite

Meteo-0 2-02
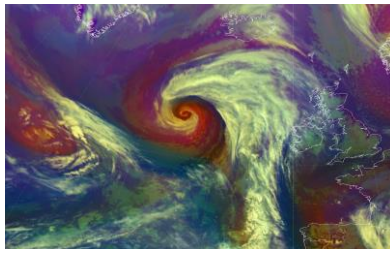
Cyclonic storm over the North Atlantic (Meteosat-9 Airmass RGB, 19/05/08 12:00 UTC)	Major dust outbreak from Northern Africa towards Greece, Turkey, Russia and Kazakhstan (Meteosat-9, Dust RGB, 22/03/08 - 24/03/08)	Strong mistral and Genoa cyclone with heavy precipitation over southern Alps (Meteosat-8 RGB: VIS0.8, IR3.9r, IR10.8, 20/03/07 09:00 UTC

There is a limited number of stations of this type around the world at one to three sites per satellite system with one antenna for each satellite of the operational fleet, which sums up to around 50-60 primary ground stations operated by the GSO MetSat operating agencies. They are equipped with antennas of approximately 10 m to 18 m diameter and typically operate with a minimum elevation angle of 3 degrees. The figure of merit (*G/T*) of such stations is of the order of 23 dB/K. Typical bandwidths of the transmissions from present generation GSO MetSat networks are between 2 MHz and 20 MHz depending on the characteristics of the instrument and the modulation methods employed.

In this context, it should be noted that MetSat systems for which assignments have been notified after 1 January 2004, the band 1670-1675 MHz will not be protected against harmful interference from applications in the mobile-satellite service (MSS) and therefore no longer usable for new MetSat systems.

For next generation GSO MetSat systems currently under development and to be deployed in the timeframe 2016–2026 as outline in Fig. 1-4 the data rates and the associated bandwidth requirements for the downlink of instrument data from these GSO MetSat systems will significantly increase (up to 800 Mbit/s). Thus, higher frequencies than the band 1 670–1 698 MHz such as the bands 7 450-7 550 MHz (Raw Data Transmission on the Electro-L and FY-4 series), 8 025–8 400 MHz (GOES-R), 18.0-18.3 GHz (Region 2), 18.1-18.4 GHz (Regions 1 and 3) (Himawari and FY-4 satellites), and in particular the band 25.5-27 GHz (Main Data Acquisition (MDA) on the Meteosat Third Generation (MTG) series) will have to be used.

2.2.2   GSO MetSat data dissemination

The following §§ 2.2.2.1 to 2.2.2.6 describe the direct dissemination functions of GSO MetSat systems operated in the framework of the Global Observing System of the World Weather Watch.

2.2.2.1 Stretched Visible Infrared Spin Scan Radiometer (S-VISSR)

The S-VISSR service is operated by the Chinese GSO MetSat system Feng-Yun-2 (FY-2) series of satellites.

Data observed by the VISSR sensors are transmitted to the main operations ground stations of this Chinese GSO MetSat system. On the ground, data are pre-processed in near real-time and retransmitted via the same satellite at a lower (stretched) data rate. These data are received by S-VISSR earth stations also called medium-scale data utilization stations (MDUSs). More than one hundred receiving stations of this type are known to be in operation. The main users are meteorological services and universities.

S-VISSR transmissions are performed in the sub-band 1 683-1 690 MHz with a centre frequency at 1 687.5 MHz. The data rate of the transmission is 660 kbit/s within a bandwidth of 2 MHz. The figure of merit of reception stations is 12 dB/K with antenna sizes of around 3m, and the minimum elevation angle of antennas is 5 degrees.

2.2.2.2 Geostationary Operational Environmental Satellites (GOES) Variable (GVAR)

The United States' geostationary operational environmental satellites GOES-13, -14, and -15 transmit processed measurement data known as GVAR to a minimum of several hundred receiving stations within the combined footprint of the GOES spacecraft located at 75° W and 135° W. These include not only stations in North and South America, but also locations in New Zealand, France, Spain and Great Britain. The majority of these recipients are universities and government agencies involved with meteorological research or forecasting. Others include value-added providers supplying weather forecasts to commercial interests. The data stream, transmitted at 1 685.7 MHz with a bandwidth near 5 MHz, consists primarily of images and sounder data with added calibration and navigation information as well as telemetry, text messages, and various auxiliary products.

With the new Generation of GOES satellites, starting from GOES-R, the GOES ReBroadcast (GRB) at 1 686.6 MHz replaces the existing GOES Variable (GVAR) service, requiring a larger bandwidth to accommodate the much increased data rates in the order of 30 Mbit/s as opposed to GVAR with around 2 Mbit/s. The GVAR currently operates at 1 685.7 MHz requiring 4.22 MHz bandwidth, while GRB will need either 9.7 or 10.9 MHz to transmit the processed data and will operate at 1 686.6 MHz.

2.2.2.3 Weather Facsimile (WEFAX)

The remaining analogue WEFAX service still operational on some GSO MetSat satellites is in the process of being replaced by digital low rate information transmission (LRIT) service on second-generation meteorological satellite systems. The WEFAX service consists of analogue transmissions to low-cost meteorological user stations within the reception area of meteorological satellites. The WEFAX service parameters were defined and agreed by the Co-ordination Group for Meteorological Satellites (CGMS), a forum for the exchange of technical information on geostationary and polar-orbiting meteorological satellite systems.

The weather facsimile (WEFAX) service on GOES-13, -14, and -15 at 1 691 MHz (586 kHz) will be combined with the Low Rate Information Transmission (LRIT) and the Emergency Managers Weather Information Network (EMWIN) currently operating at 1 692.7 MHz (27 kHz) into a single downlink known as HRIT/EMWIN, where the HRIT replaces LRIT. The new combined service will transmit at 1 694.1 MHz, requiring 1.21 MHz of bandwidth. The existing sensor data downlink at 1 676 MHz will be moved to 8 220 MHz within the EESS X-band (8 025-8 400 MHz) to accommodate the greatly expanded data rates from the advanced sensors on-board the GOES-R spacecraft.

The World Meteorological Organization (WMO) has registered several thousands of WEFAX reception stations around the world, however, as in the case of GVAR and S-VISSR receivers, it is not known exactly how many receivers are actually in use. WEFAX reception stations are essential equipment for the operation of smaller and mid-sized meteorological services and are also used by universities, environmental agencies, press agencies, schools and others.

The transmission of WEFAX services is in the sub-band 1. The remaining WEFAX services have a centre frequency of 1 691 MHz and a bandwidth between 0.03 MHz and 0.26 MHz. Typical WEFAX reception stations operate at elevation angles greater than 3 degrees, and use antennas of 1.2 m diameter with a figure of merit (*G/T*) of 2.5 dB/K. Content of WEFAX transmissions are sectors of satellite imagery, meteorological products in pictorial presentation, test images and administrative messages containing alphanumerical information in pictorial form.

2.2.2.4 Low Rate Information Transmission (LRIT)

LRIT is a service that was initiated in 2003 on GOES geostationary meteorological satellites for transmission to low cost user stations. This service was intended to replace the WEFAX service on other GSO MetSat satellites, serving a similar user community.

Transmissions of LRIT are performed in the sub-band 1 690-1 698 MHz with centre frequencies around 1 691 MHz. The bandwidth is up to 660 kHz. User station antennas have diameters between 1.0 m and 1.8 m and are operated with a minimum elevation angle of 3 degrees. The figure of merit for LRUS is 3-6 dB/K depending on the user station location. LRIT is operational on many MetSat systems, namely the GOES

satellites, the Meteosat second generation satellites, the COMS-1 satellite (to be continued by the GEO-KOMPSAT-2A satellite), the Himawari satellites, the Electro-L satellites and on the FY-2 series of satellites from satellite FY-2E/F/G onwards and will be continued on the FY-4 series together with an Emergency Weather Alarm Information Broadcast (EWAIB).

2.2.2.5 High Rate Information Transmission (HRIT)

HRIT service was introduced in January 2004 with the operation of the first satellite of the Meteosat second generation series satellites (Meteosat-8) and is operational on many MetSat systems, namely the Himawari satellites, the COMS-1 satellite (to be continued by the GEO-KOMPSAT-2A satellite), the Electro-L satellites and the future FY-4 series. Also the series of GOES satellites from GOES-R onwards will operate an HRIT/EMWIN service.

The HRIT service is operated in the sub-bands 1 675-1 687 MHz, 1 684-1 690 MHz or 1 690-1 698 MHz. The antenna size for high rate user station (HRUS) and MDUS is 4 m or smaller and the minimum elevation angle is 3 degrees. The figure of merit for the user stations is 12-14 dB/K depending on the user station location.

A new Direct Broadcast Global Specification (GEO HRIT/LRIT) has been published within 2013 by CGMS. This Direct Broadcast specification is applicable to existing and planned GEO systems, however not specifying user station characteristics. Work continues within CGMS to assess the need for further updating the GEO global specification in view of newly available and used standards on telecommunications and file formats.

2.2.3 GSO MetSat Data Collection Platforms (DCPs)

Data collection systems are operated on meteorological satellites for the collection of meteorological and other environmental data from remote DCPs. Transmissions from each DCP to a meteorological satellite are in the frequency band 401-403 MHz. DCPs are operated in time sequential mode. The transmission time slots are typically 1 min. Transmission rates are 100 bit/s. Higher data rate DCPs (300 bit/s and 1 200 bit/s) began operation in 2003 and are expected to increase rapidly in the near future. Channel bandwidths of these high rate DCPs are 0.7510 kHz or 2.2510 kHz for 300 and 1 200 bit/s, respectively.

There are various types of DCP transmitters in operation generally ranging from 5 W, 10 W and 20 W output power with a directional antenna, or 40 W output power with an omnidirectional antenna. The resulting uplink equivalent isotropically radiated power (e.i.r.p.) is between 40-52 dBm. Data collection systems are currently operated on various geostationary meteorological satellite systems.

The DCPs reporting to geostationary MetSats use frequencies in the 401.1-402.85 MHz range, with 402.001-402.067 MHz for international use (22 channels of 3 kHz in bandwidth). By using narrow bands (as small as 0.75 kHz) and by shortening the reporting times to typically 10 s, it is possible to receive data from a large number of these platforms. For example, in the case of the GOES-13, -14, -15 satellites, in 2016 there were around 27 000 GOES high rate DCPs in operation, sending up to 400 000 messages per day, delivering more than 6 million observations into the GOS daily. These numbers are anticipated to further increase.

2.2.3.1 Basic general partitioning and sharing conditions for the band 401-403 MHz

The increased spectrum requirements of DCS systems on both, geostationary and non-geostationary, MetSat and EESS systems require all operators to respect a basic general partitioning of the band 401-403 MHz for current and future DCS systems (see Fig. 2-3) accompanied by sharing conditions as outlined in Recommendation ITU-R SA.2045.

FIGURE 2-3

**Basic general partitioning of the band 401-403 MHz for future long-term coordinated use of DCS systems
on geostationary and non-geostationary MetSat and EESS systems**
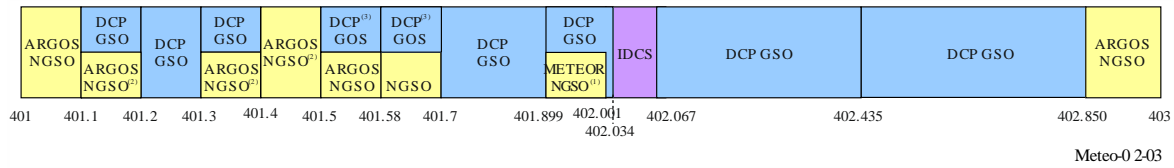
Meteo-0 2-03

2.3   MetSat systems using non-GSO satellites

Beside the numerous GSO MetSat satellites, non-GSO MetSat systems complement the satellite-based contribution to the Global Observing System through global coverage measurement data from a variety of passive and active sensors observing in the visible, infrared and microwave spectral regions.

The continuous and long-term coverage of observations from the non-geostationary orbit will be ensured through the operation of current and future satellites operated by a number of national and regional meteorological organizations throughout the world (see Figs 1-3 and 1-4).

Figure 2-4 provides examples of an Advanced Very High Resolution Radiometer (AVHRR) flown on operational non-GSO MetSat systems taking global visible, near-infrared and infrared imagery of clouds, oceans and land surfaces. Examples of passive and active sensors observing in the microwave spectral region operated on non-GSO MetSat systems are provided in Chapter 5.

FIGURE 2-4

Samples of image by an advanced very high resolution radiometer
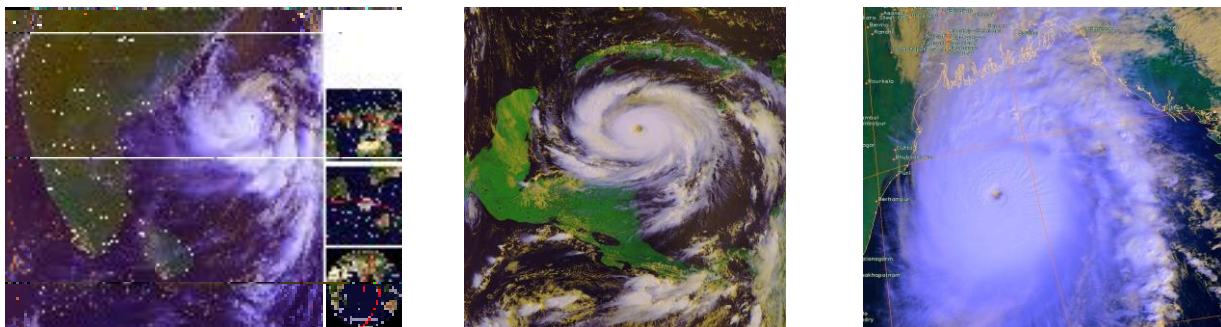
Meteo-02-04

2.3.1   Non-GSO MetSat raw instrument data transmissions

Raw data from the currently operational non-geostationary meteorological satellites, mostly polar-orbiting, are transmitted in the frequency band 7 750-7 900 MHz or 8 025-8 400 MHz, depending on the bandwidth required, to main stations located at high latitudes. The transmission takes place in bursts as each satellite overpasses its main station, with the transmitters switched off at other times.

2.3.1.1 Non-GSO MetSat raw instrument data transmissions using the band 25.5-27 GHz

Some future non-GSO MetSat systems (for example the EUMETSAT Polar System – Second Generation (EPS-SG) with its Metop-SG satellites and the satellites of the Joint Polar Satellite System (JPSS)) will need to use even higher frequency bands than those used by the currently operational satellites, i.e. the band 25.5-27 GHz, to be able to transmit the significantly increased data rates of up to 800 Mbit/s to its main ground

stations. This link is called Stored Mission Data (SMD) downlink.). Others will use the frequency band 8 025-8 400 MHz (e.g. current FY-3, METEOR and Suomi-NPP).

2.3.2 Non-GSO MetSat data dissemination

Sections 2.3.2.1 to 2.3.2.4 describe the direct dissemination functions of non-GSO MetSat systems operated in the framework of the Global Observing System of the World Weather Watch.

2.3.2.1 Non-GSO MetSat data dissemination using the band 1 698–1 710 MHz

2.3.2.1.1 Automatic Picture Transmission (APT)

The Automatic Picture Transmission (APT) service was introduced on some spacecraft already in the 1960s and became the most successful direct data dissemination system in the meteorological community. Thousands of such APT receiving stations are still in operation worldwide. APT stations are very low cost and are operated not only by meteorological services and universities but also by a large community of non-meteorological users.

APT stations typically consist of omnidirectional antennas and commercial-off-the-shelf (COTS) VHF receivers. Low cost image processing systems are attached to this front-end, with low-priced software running on commonly available desktop computers. APT is operational on the NOAA satellites and the series of METEOR-M N2 satellites.

2.3.2.1.2 Low Resolution Picture Transmission (LRPT)

The LRPT service was supposed to replace the APT application on most non-GSO MetSat systems. However, the only series of satellites of which the LRPT service was implemented and operational is METEOR-M N2. LRPT is based on digital transmission schemes and makes use of the same frequency bands as those currently used for APT. The bandwidth is also up to 175 kHz.

2.3.2.1.3 High Resolution Picture Transmission (HRPT)

The HRPT service provides high-resolution imagery to the meteorological community. HRPT transmitters are turned on continuously and can be received by any user station. There are hundreds of HRPT receiving stations worldwide registered with the WMO. However, it should be noted that this number is not all-inclusive since registration of these stations is not mandatory. HRPT data are essential to operations of meteorological services and are widely useful in other endeavours as well.

In the HRPT service like on the NOAA satellites (1 698/1 702.5/1 707 MHz) transmissions are performed in the frequency band 1 698-1 710 MHz with signal bandwidths between 2.7 MHz and 4.5 MHz. User stations are equipped with tracking parabolic antennas typically between 2.4 m and 3 m in diameter. The recommended minimum elevation angle for reception is 5 degrees, although some stations operate at elevation angles lower than this. The figure of merit for stations is 5 dB/K. There are other HRPT systems that operate at data rates that are about twice the rate of the original HRPT systems.

There is also an Advanced HRPT (AHRPT) application on some of the latest operational meteorological satellites, i.e. the series of METEOR-M N2 (1 700/1 705 MHz), Metop (1 701.3/1 707 MHz) and FY-3 (1 701.3 MHz, 1 704.5 MHz or 1 706.7MHz) satellites that is intended to replace the HRPT service. AHRPT transmissions use the same band as the other HRPT systems. The bandwidth ranges between 4.5 and 6.8 MHz. AHRPT reception stations receive with minimum elevation angles of 5 degrees. Antennas are parabolic with typical diameters between 2.4 m and 3 m. The *G*/*T* of AHRPT stations is around 6.5 dB/K.

In the framework of the Coordination Group of Meteorological Satellites (CGMS) a new Direct Broadcast Global Specification (LEO Direct Readout (HRPT/AHRPT)) has been published within 2014 by CGMS. This Direct Broadcast specification is applicable to existing and planned LEO systems, however not specifying user station characteristics. Work continues in CGMS to assess the need for further updating the LEO global specification in view of newly available and used standards on telecommunications and file formats.

2.3.2.2 Non-GSO MetSat data dissemination using the band 7 750-7 900 MHz

The trend for more and higher resolution data also requires to use higher frequency bands for the direct dissemination of instrument data to user stations as the corresponding bandwidth requirement for such high resolution data cannot be satisfied in the band 1 698-1 710 MHz. Thus, the next higher available frequency band allocated to MetSat in the space-to-Earth direction that has to be used is the band 7 750-7 900 MHz. In this band the bandwidth requirements of the new generation non-GSO MetSat systems, ranging from 30 to 150 MHz for the different downlinks (MPT (FY-3), High Resolution Data (HRD) (Suomi-NPP and JPSS) and Direct Data Broadcast (DDB) (Metop-SG)) can be satisfied.

The Medium-resolution Picture Transmission (MPT) provides a full set of data of the MERSI instrument measurements on-board the FY-3 series of satellites. The current FY-3 satellite data rate of the transmission is a 18.7 Mbit/s within a bandwidth of 45 MHz centred at 7 775 MHz, or the data rate of the transmission is a 45 Mbit/s within a bandwidth of 60 MHz centred at 7 780 or 7 820 MHz. In addition, on the FY-3 series a Delayed Picture Transmission (DPT) service is provided for dump data transmission at 8 145.95 MHz with a bandwidth of 149 MHz at a data rate of 93 Mbit/s, or at 8 175 MHz and 8 125 MHz with a bandwidth of 300 MHz at a data rate of 225 Mbit/s. The High Rate Data (HRD) is a broadcast of a full resolution data set from Suomi-NPP and the series of JPSS satellites of up to the 15 Mbit/s data rate (30 MHz bandwidth) with its centre frequency at 7 812 MHz. The Direct Data Broadcast (DDB) on the Metop Second Generation (Metop-SG) series of satellites will broadcast at 7 825 MHz with a bandwidth of 150 MHz.

2.3.3   Non-GSO MetSat Data Collection Systems (DCSs)

Data collection systems on non-GSO MetSat satellites provide a variety of information used principally by governmental agencies but also by commercial entities.

Such data include a number of environmental parameters for oceans, rivers, lakes, land and atmosphere related to physical, chemical, and biological processes. It also includes animal tracking data. However use by commercial entities is limited. It comprises, for example, monitoring of oil pipeline conditions in order to protect the environment or maritime security. Some transmitters are also deployed to report emergencies and supply data such as for hazard/disaster recognition. Examples of Data Collection Systems operated from non-geostationary meteorological satellites are Argos and Brazilian DCS. The third generation of Argos (Argos-3) is already operational on the series of Metop satellites, NOAA-19 and a SARAL satellite.

These NOAA, Metop and SARAL satellites follow a polar orbit at 850 km altitude: they pass over the North and South poles at each revolution. The orbit planes turn around the poles axis at the same speed than the Earth around the Sun. Each satellite sees simultaneously and at all time all the beacons inside a circle of about 5 000 km in diameter. With the movement of the satellite, the ground track of this circle forms a band of 5 000 km wide which wrap around the Earth while passing at the North and South poles.

Currently, the Argos system operates in the 401.579-401.690 MHz band, though thousands of platforms (known as platform transmitter terminals), each requiring only few kHz of bandwidth. Taking advantage of the nature of the orbits of polar-orbiting satellites, it is possible to accommodate many Argos platforms. About 22 000 platforms are in operation. Each platform is characterized by an identification number which is unique and depends on its transmission electronics.

The transmission duration of each message is less than one second. The Argos-3 system generation introduces new data collection services offering high data rate (4 800 bit/s) and platform interrogation capability. Depending on the bit rate, the values of output power of platform range from −3 dBW up to 7 dBW.

The platform known as PMT (Platform Messaging Transceiver) is interrogated by satellites using the 460-470 MHz band and is currently performed at 465.9 MHz.

For the fourth generation of the Argos system (Argos-4), it is expected that the system capacity and the bandwidth will have to be significantly increased using other frequency bands as shown in Fig. 2-3. In addition, the new Argos 4 system will implement a downlink within the 464.98775-466.98775 MHz frequency band and a spread spectrum multiple access will be implemented in order not to cause interference to terrestrial users.

The Brazilian DCS is based on SCD (25° inclination orbit) and CBERS satellites using 401.605-401.665 MHz band for data collection platform reception. Due to the compatibility between the Brazilian DCS with the Argos system and complementary orbit satellites, data exchange between both systems has been implemented since 2001.
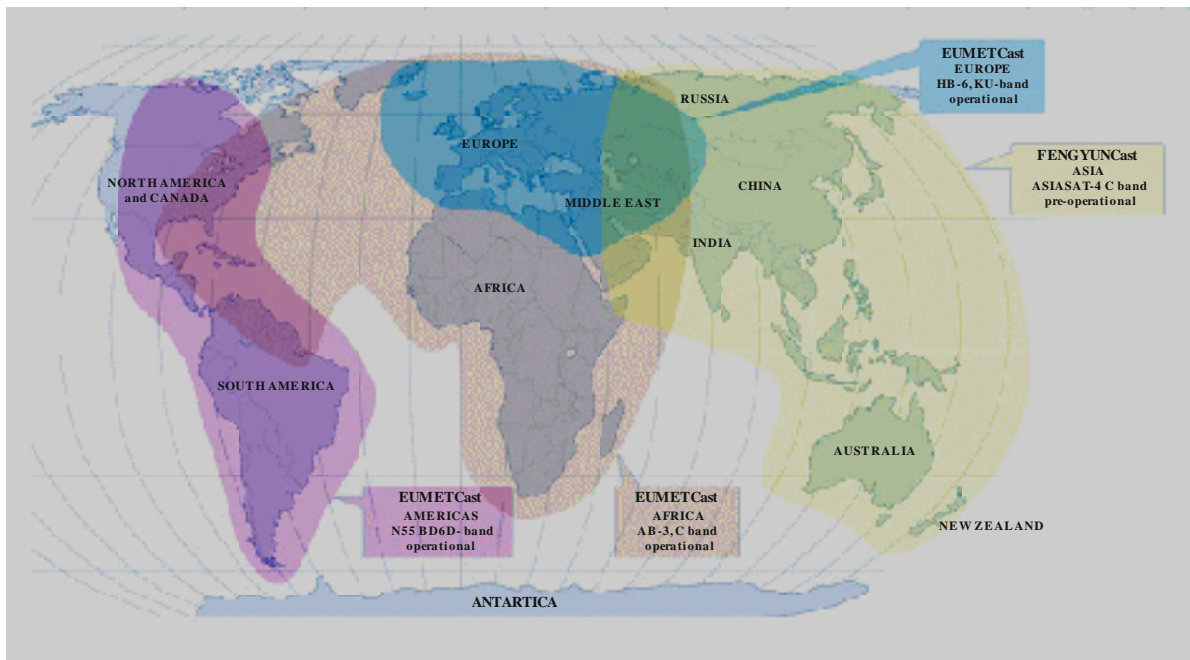
2.4   Alternative data dissemination mechanisms

Beside the traditional dissemination mechanisms of GSO and non-GSO MetSat systems an additional dissemination system is in the process of establishment, called GEONETCast (see Fig. 2-5), which is a major Global Earth Observation System of Systems (GEOSS) initiative to develop a worldwide, operational, end-to-end Earth observation data collection and dissemination system, using existing commercial telecommunications infrastructure. The GEONETCast concept is to use the multicast capability of a global network of communications satellites to transmit environmental satellite and *in situ* data and products from providers to users. To achieve this several regional centres take on the responsibilities for establishing and maintaining a satellite-based regional dissemination system, based upon Digital Video Broadcast (DVB) technology, and provide complementary services to a common user community. Current partners include the China Meteorological Administration (CMA), the National Oceanic and Atmospheric Administration (NOAA), the World Meteorological Organization (WMO) and EUMETSAT, as well as many prospective data provider partners.

The global coverage is provided through the integration of the CMACast system, covering the Asia Pacific region, the GEONETCast Americas component, covering the Americas and the EUMETCast system, covering Europe, Africa and the Americas.

FIGURE 2-5

Global GEONETCast coverage

Meteo-0 2-05

CHAPTER 3

METEOROLOGICAL AIDS SERVICE

Page

3.1   Introduction

The meteorological aids (MetAids) service is defined in No. 1.50 of the Radio Regulations (RR) as a radiocommunication service used for meteorological, including hydrological, observations and exploration. This Chapter only covers the upper air *in situ* observation, other MetAids applications being covered in Chapter 6 of this Handbook.

In practice, MetAids service usually provides the link between an *in situ* sensing system for meteorological parameters and a remote base station. The *in situ* sensing system may be carried, for instance, by a weather balloon. Alternatively, it may be falling through the atmosphere on a parachute after deployment from an aircraft or meteorological rocket. The base station may be in a fixed location, or mounted on a mobile platform as used in defence operations. Base stations are carried on ships, and carried on hurricane watch or research aircraft. The vast majority of such *in situ* sensing systems are radiosondes most of which are launched regularly from fixed locations and a small number of commercial ships, forming global WMO GOS upper-air network, according to fixed world-wide schedule (00, 06, 12 and 18 UTC) established by WMO.

3.1.1   Allocated RF bands

The frequency bands that are used for MetAids service (other than those governed by national footnotes) are shown in Table 3-1[1].

TABLE 3-1

Frequency bands used for MetAids systems/applications

Frequency band
400.15-401 MHz
401-402 MHz
402-403 MHz
403-406 MHz
1 668.4-1 670 MHz
1 670-1 675 MHz
1 675-1 690 MHz
1 690-1 700 MHz
35.2-36 GHz

There are also other primary services in these bands which placed significant constraints on the MetAids service. Co-channel sharing between other services and the MetAids service is rarely feasible because of the low power transmissions used by most MetAids systems for relatively long-range links. Hence, most band sharing relies on band segmentation. This may be organized internationally with other meteorological systems through the auspices of WMO, or at a national level with the non- meteorological systems.

WMO regularly updates a catalogue of radiosonde systems in use within the WMO network (WMO No.9, Vol.A, which is being superseded now by OSCAR/Surface WIGOS metadata repository), so that the meteorologists using the measurements are able to identify the type of radiosonde in use at each station. This catalogue includes a record of the frequency band used.

Users of the MetAids service also include:

–   environmental agencies

–   universities and meteorological research groups

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[1]   For current frequency allocation in these bands, the reader is referred to Article 5 of the RR.

–   defence services.

These additional systems are usually operated independently from the routine operations of the national meteorological services and are not listed in the WMO catalogue. Many of the non-WMO MetAids systems are mounted on mobile platforms and may be deployed over a wide range of locations during operational use. The number of radiosondes sold to these independent groups is similar to the number used in the routine WMO network. The operation of the additional systems is not usually regulated by the national radiocommunication authorities.

In some countries co-channel sharing between all the different groups of radiosonde operators is avoided by using a detailed channel plan. However, in many countries a pragmatic approach to spectrum use is still used. Before launching the radiosonde, the radiosonde system operator scans the available MetAids spectrum using the base station receiver. This identifies if there are any radiosondes already in use near the launch site. The frequency of the radiosonde to be launched is then selected (tuned as necessary before launch) so that it will function without detriment to the systems already in flight. The available MetAids spectrum for a national MetAids service is often limited to a sub-band of that allocated in the RR because of national sharing agreements with other radiocommunication services, as noted earlier.

Commercially available radiosonde systems operate in the WMO network in the 400.15-406 MHz and 1 668.4-1 700 MHz frequency bands. The reasons for the continued use of these two MetAids service bands is discussed in a later section, once the systems in use have been discussed in more detail.

3.1.2   Meteorological functions of the MetAids service

Accurate measurements of the variations with height in atmospheric temperature, pressure, relative humidity, and wind speed and direction are essential for operational meteorology. These measurements define the basic characteristics of weather systems so that the forecaster can judge what is likely to happen in the short term. They also provide the input for numerical weather prediction models that are used in longer-term forecasts. They are further used for climate monitoring purposes. Short-term forecasts require high vertical resolution in temperature and relative humidity measurements. For instance, the position of clouds near the surface needs to be measured with an accuracy of better than 100 m in the vertical.

The MetAids service has been the main source of atmospheric measurements with high vertical resolution for many decades. In addition, these *in situ* measurements are essential for calibrating space-borne remote sensing, in particular passive. MetAids transmit *in situ* measurements of atmospheric meteorological variables from locations above the surface to a base station consisting of a receiver and data processing system. In most cases, pressure (or height), temperature, relative humidity, and wind speed and direction are measured. Measurements of atmospheric constituents such as ozone, aerosol or radioactivity may also be included. The output from the base station is transmitted to the meteorological communications networks for integration with data from other receiving stations . The MetAids are not usually recovered after use, so the cost of the transmitter and sensing package must be kept to a minimum.

In the most commonly used MetAids system, an operational radiosonde can be carried by a weather balloon to heights of up to 36 km above the surface where the balloon bursts. The height to which regular observations are required varies to some extent with the application and geographical location and, for many countries, is limited by cost of balloons and lifting gas required. In many countries, routine meteorological operations aim for a height of about 25 km above the surface, although some stations need to measure heights above 30 km. Forecasting on a global scale needs to take into account the movements of the atmosphere at the upper levels, but not in as much detail as the conditions closer to the surface. However, long-term climate monitoring and associated scientific research need high resolution measurements from as high in the upper atmosphere as practicable.

Radiosonde measurements are transmitted for up to two hours to a base station located at the balloon launch site. The balloon moves with the upper atmospheric winds during this time and on occasions may travel more than 250 km from the launch site during ascent. During descent, they may travel an additional 150 km. Descent data are considered to be of potential value as well. The transmission power is always low, because of the limitations imposed by the available batteries. The batteries must function at the very low temperatures encountered during a flight, and must also not damage the environment or endanger public safety when falling to earth after the balloon bursts.

Every day more than 1 400 radiosondes are launched in the WMO GOS network; of these radiosondes at least 400 are for measurement at nominated GCOS (Global Climate Observing System) sites. The information from each operational radiosonde is immediately used by national meteorological services to support local forecasting. This information is also required for numerical weather forecasts for all parts of the world, and the goal is to circulate the completed message reports (in standardized meteorological code) to all meteorological services around the world within three hours. The messages are also archived permanently and are then used in a wide range of scientific investigations. Other MetAids systems currently deployed in more limited numbers include:

Type	Description
Dropsondes	Dropped from high flying aircraft using a parachute, with the dropsondes usually transmitting back to a receiving station on the aircraft for about half an hour
Tethersondes	Transmits back continuously from a tethered balloon usually within the atmospheric boundary layer
Rocketsondes	Transmits atmospheric measurements at heights up to 95 km for specialized scientific investigations or launched from ships for low-level measurements
Small pilot less aircraft (remotely piloted vehicle (RPV) or unmanned aerial vehicle (UAV))	Carries a similar sensor package to the radiosonde to remote areas over the ocean and also transmits information back as a standard meteorological message

Apart from operational GOS, defence and research applications MetAids are used for weather reconnaissance for mitigating natural and industrial disasters.

The current cost of performing radiosonde measurements limits the optimum spacing of the operational radiosonde network to 250 km in the horizontal direction. This spacing, which takes into account balloon drifts, is used as the standard for network studies on the radio spectrum required for the MetAids operational service. However, adequate resolution of the persistent characteristics of organized weather systems needs measurements with spacing in the horizontal direction of 50 km or less. Meteorological research requires radiosonde or dropsonde measurements at this spacing. In the future, frequency allocations need to facilitate both operational radiosonde use and those of the research communities.

While the number of active operational radiosonde stations in the GOS network is decreasing slightly with time, this is being compensated for by an increased use of radiosondes for environmental and defence services. In addition, there is a requirement from national meteorological services for more *in situ* measurements in targeted areas over the ocean. A significant increase in the use of newer types of MetAids systems can be expected in the next decade to support these expanding requirements.

## 3.2   Examples of MetAids sensing systems

3.2.1   Radiosondes

More than 800 000 radiosonde flights are carried out each year worldwide (Figs 3-1 and 3-2). In addition another 400 000 flights are made for various other applications. The base station sites used to launch the radiosondes are usually specially equipped so that the balloons can be launched in all weather conditions. The most critical sites are equipped with emergency power supplies and accommodation so that the measurements can continue even if the local infrastructure is damaged by extreme weather or other circumstances such as an industrial accident.

FIGURE 3-1

A radiosonde flight train

Meteo-03-01

FIGURE 3-2

Radiosondes
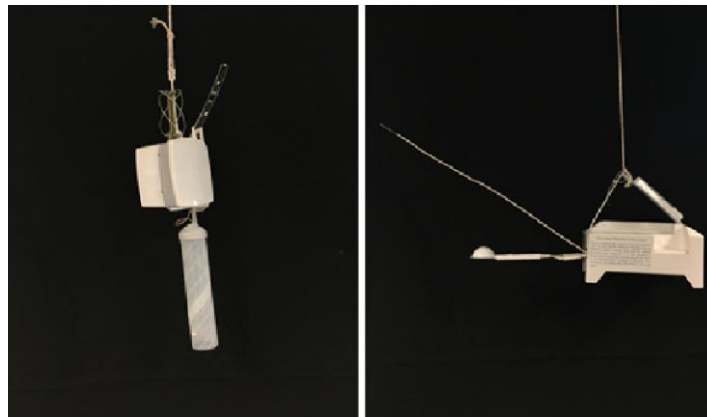
Meteo-03-02

A typical radiosonde contains several major components: a transmitter, battery, sensor pack, and usually a navigational aids (NAVAID/GNSS (e.g. GPS) receiver (Fig. 3-3). The transmitter transmits the data to the receiving station. Radiosondes typically use lithium or alkaline batteries that can withstand temperatures of $-90°$ C. The sensor pack contains the sensors that measure the atmospheric conditions such as temperature, pressure, humidity, and in special cases ozone or ionising radiation. The sensor pack also encodes the sensor values sufficiently to transmit them to the ground station.

Radiosonde systems measure winds by tracking their balloon's motion through the atmosphere. Active tracking systems use primary (tracking of a reflector for radar signals suspended below the balloon) or secondary (tracking of a transponder integrated into a radiosonde) radar tracking. Passive tracking system use NAVAID/GNSS receivers or, in some coast areas, LORAN-C retransmitters on the payload and transmit this data to the ground station, or radiotheodolite tracking of radiosonde signals.

FIGURE 3-3

Modern radiosonde electronics
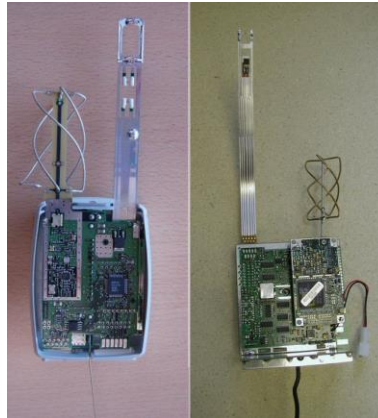
Meteo-03 -03

3.2.2   Dropsondes

Dropsondes have components similar to radiosondes, but are built such, that they can be dropped from aircraft to profile the atmosphere while descending under a parachute. See Fig. 3-4. Since operation of a large tracking antenna is impractical on aircraft, all dropsondes are operated in the 401-406 MHz band and utilize NAVAID/GNSS for wind measurement. Operationally, dropsondes are deployed at a much higher density in space and time than radiosondes. They are primarily used in tracking and profiling tropical storms at sea. As many as 16 dropsondes may be placed in flight and tracked simultaneously. The high density of deployment necessitates the use of highly stable narrow-band transmitters, similar to those used in the denser parts of the radiosonde network. Dropsondes are also used for profiling weather phenomena or the basic atmospheric state in remote oceanic regions, and occasionally over land.

FIGURE 3-4

A dropsonde

Meteo-03 -04

3.2.3   Rocketsondes

Rocketsondes are a more specialized MetAids system. Like the dropsondes, they are released from rocket that has reached a high altitude and profile the atmosphere during a parachute-controlled descent. Rocketsondes may contain the same basic components as radiosondes, but the sensing packages for high altitude measurements may differ from those systems used in the lower parts of the atmosphere. Unlike dropsondes, they may employ either radio direction finding or NAVAID/GNSS for wind measurement. Most rocketsondes are launched to very high altitudes and are typically used in support of space launch operations (see Fig. 3-5). Because the deployment of the rocketsondes is expensive, the use of higher quality transmitters is necessary.

FIGURE 3-5

A rocketsonde
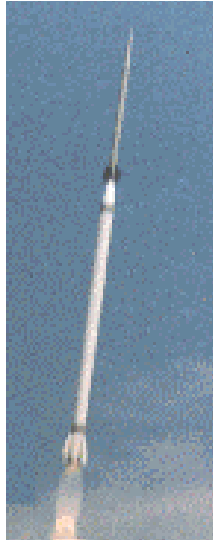
Meteo-03 -05

3.3   Factors influencing the characteristics of the MetAids systems

MetAids systems are comprised of several basic radiocommunication components. The ground portion of the system typically contains an antenna/receiver system and a signal processing system. Recommendation ITU-R RS.1165 – Technical characteristics and performance criteria for radiosonde systems in the meteorological aids service, contains descriptions and technical parameters of the various types of systems used for MetAids operations.

3.3.1   Ground-based receiver antenna system

Radiosondes, dropsondes and rocketondes use a radio frequency link to transmit the data back to the antenna/receiver system located at the data processing location. The two bands that are mostly used for this purpose are 400.15-406 MHz and 1 668.4-1 700 MHz. Typically the antenna/receiver system is ground based (for radiosondes and rocketsondes), but in the case of dropsondes the antenna/receiver system is located on an aircraft. The particular antenna receiver system configuration varies based on the operating band and the maximum flight slant range expected. Omni-directional antennas and rosettes of Yagi antennas or corner reflectors are typically used for systems operated in the band 400.15-406 MHz (see Fig. 3-6). Very high antenna gain is not needed by these types of antenna to maintain the RF link. Radio direction finding (RDF) is not used for measuring the winds in this band. The antenna gain of the antenna systems operated in the band 400.15-406 MHz range from 0 dBi to 10 dBi.

FIGURE 3-6

Omni-directional antenna and directional systems (401-406 MHz)
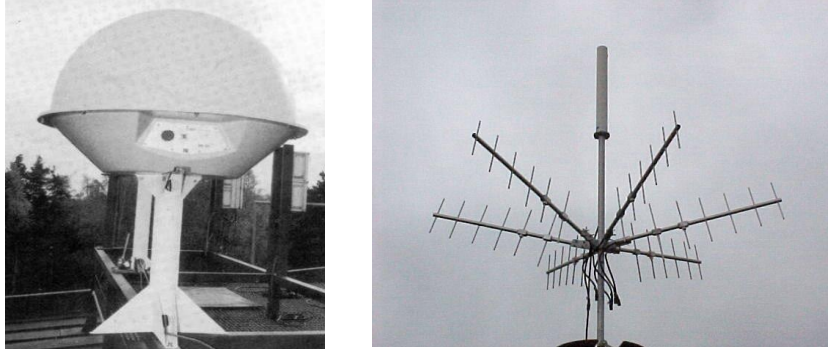
Meteo-03 -06

Wind measurement is usually accomplished through RDF or radar tracking in the 1 668.4-1 700 MHz band. Some countries still prefer using RDF to track a radiosonde providing windfinding with a built-in NAVAID/GNSS receiver – this allows alternative using a radiosonde without a built-in NAVAID/GNSS receiver with windfinding from RDF. Therefore, tracking pedestals equipped with large parabolic antennas or phased array panels are used to avoid path loss (see Fig. 3-7). The antenna pedestal rotates the antenna in azimuth and elevation to track the MetAid movement. Antenna gains of 25-28 dBi are typical for antenna systems operated in the band 1 668.4-1 700 MHz.

FIGURE 3-7

Tracking antenna systems (1 668.4-1 700 MHz)

Meteo-03 -07

3.3.2   Ground-based processing system

The receiver passes the baseband radiosonde signal to a signal processing system that decodes the analogue or digital radiosonde data and generates the required atmospheric measurement data, including winds. Some MetAids do not transmit the actual meteorological values (pressure, temperature, humidity, ozone, winds, etc.) to the receiving station but rather transmit the electronic characteristics of the sensors, NAVAID/GNSS data to minimize the cost of processing on the MetAid. The signal processing system on the ground then applies the capacitive and/or resistive sensor values and sensor calibration values, to a polynomial to calculate the meteorological parameter. Other MetAids may perform most signal processing within the MetAids and transmit actual meteorological values and winds directly. In this case the processing system on the ground may perform only a subset of the overall data processing.

3.3.3   Expendable sensing packages

The nature of the MetAids service operations places constraints on how they are manufactured. Most of the design constraints impact the radio frequency characteristics of MetAids expendables and hence the spectrum requirements of MetAids operations. The most significant constraint is the production cost of the devices. However, other constraints such as density, mass, operating environment, and power efficiency are also major concerns to manufacturers and operators.

Production cost is usually the first issue raised in a discussion on implementing more spectrally efficient transmitters. Radiosondes are expendable devices. They are typically flown once and lost; though a small number are recovered and reconditioned for reuse. There is a need to minimize the complexity of the circuitry as much as possible to minimize cost. Advancements in technology have provided some opportunity to use cost effective integrated circuits to improve radiosonde performance. Historically, many of the improvements applied to radiosondes have been to improve measurement accuracy of the sensors. In recent years, operators have been forced to implement some improvements to the RF characteristics in order to increase network density. This resulted in that most world-leading manufacturers' radiosonde designs comply with quite stringent ETSI standards in respect to emission bandwidth and sideband radiation. Many basic radiosonde designs contain single stage transmitters. These designs are affected by changes in temperature, battery voltage, and capacitive loading of the antenna during handling. Use of commercially available application specific integrated circuits (ASICs) is now increasing as suitable devices that can be operated over the extreme temperature ranges.

The density of MetAids expendables must be limited for safety reasons. The mass of the MetAids expendables is also limited for both safety and operational reasons. While extremely unlikely, MetAids must be designed to ensure that a collision with an aircraft will not damage the aircraft and will not create a life-threatening situation. The density is primarily of concern if the device were to be ingested into the engine. The devices' mass is a concern since MetAids expendables drop back to the Earth's surface after a flight. A parachute is often used to control the rate of descent. However, an object with significant mass has the potential to cause damage. Most MetAids expendables now have a mass much less than 1 kg (without a balloon). Typically, radiosondes are housed in a foam, paperboard or plastic package that is lightweight and easily destructible. The circuit cards are small and contain a small number of components and the circuitry is designed for maximum power efficiency. Due to the density and mass limitations, a large battery cannot be used to power the devices.

MetAids can be exposed to a variety of extreme conditions during flight. The temperature may range from 50 °C to −90 °C, humidity can range from very dry conditions to condensation, sublimation or precipitation. At higher altitudes, insufficient air for ventilation of the electronics and solar radiation can lead to overheating even at low temperatures. These extreme changes in conditions can have a dramatic effect on the performance and characteristics of all the device components including the transmitter. It was not uncommon for an older design radiosonde transmitter to drift 5 MHz or more due to extreme temperature changes and other effects such as icing of the antenna that causes capacitive loading. Due to limitations on the power consumption and the effect that generating heat can have on sensor performance, stringent temperature control of the electronics is not practical. In addition, it has been found that many of the commercially available transmitter integrated circuits used by the wireless telecommunications industry cannot operate at the extremely low temperature.

The power consumption of the MetAid electronics must be carefully managed in the design. Large batteries increase the weight causing a potential safety hazard, and the additional weight increases operational costs by requiring larger balloons and larger amounts of gas for balloon inflation. Power efficiency is the primary reason that MetAids are designed to use as little transmitter output power as possible and still maintain a reliable telemetry link. Radiosonde transmitters typically produce 100-400 mW and the link budget at maximum range only has on the order of 0.5-2 dB of link margin. The commonly used single stage transmitter has been found to be very power efficient, while the more advanced transmitter designs have been found to consume 150-250% more power than the single stage transmitter. However, these single stage transmitters are vulnerable to the extreme temperature changes and capacitive loading of the antenna during handling resulting in large frequency drift. For this reason, the more spectral efficient transmitter designs impact both transmitter manufacturing costs and the cost of the associated electronics.

3.4   Characteristics of meteorological observations required from the MetAids service

The characteristics of observations required from MetAids service operations are illustrated in this section with a few examples of radiosonde measurements.

Figure 3-8 shows temperature and relative humidity measurements as a function of height, in a measurement from a climate monitoring site at 60° N in the UK (Lerwick, Shetland Islands, 23 January 2000). Radiosonde temperature measurements have small errors, less than 0.5 °C at heights up to 28 km, and are well suited for climate monitoring. In this observation, the temperature decreased at a relatively uniform rate from the surface to a height of about 12 km. This level is designated as the tropopause by meteorologists and represents the boundary between the air interacting with the Earth's surface, and the air in the stratosphere where there is minimal interaction with the surface layers. Between the surface and the top of the tropopause, there were relatively thin layers where the temperature either increased slightly with height or fell at a very slow rate. The relative humidity also dropped very rapidly as the MetAid ascended through these layers. Significant drops occurred at heights of 1.8 km and 4 km in layers that would be termed temperature inversions by forecasters. In addition, there were also less pronounced changes in the temperature lapse rate near 8 km and 10.3 km, again associated with a significant reduction in relative humidity with height. The variations in the rate of change of temperature and humidity in the vertical affect the propagation of radio waves in the atmosphere. Thus, MetAids observations are also well suited to identifying radio propagation conditions.

The balloons lifting the radiosondes are designed to provide optimum performance when ascending at about 300 m/min. Any significant loss of reception early in an ascent (even for 10 s) is undesirable since this compromises the ability of the radiosonde to resolve the changes in temperature and relative humidity near the surface, required for local forecasting. Missing data for four or five minutes (even if only caused by faulty navigation signal reception for the wind measurements) often necessitates the launch of a second radiosonde to fulfil the operational requirement.

The observation shown in Fig. 3-8 is typical since relative humidity measurements were from 5% to 90% between the surface and the level where the temperature falls below −40 °C. By the time the temperature fell below −60 °C at 10 km, the response of the relative humidity sensor was becoming too slow to fully resolve rapid changes in relative humidity. This reflects a marked improvement in radiosonde relative humidity sensor performance since the 1980's. All earlier relative humidity sensors became unreliable at temperatures between −30 °C and −40 °C. The relative humidity sensor is the most difficult to manufacture and has proved to be one of the main barriers to designing and manufacturing a radiosonde without extensive long-term investment in design and production facilities.

FIGURE 3-8

Temperature and humidity measurement by a radiosonde
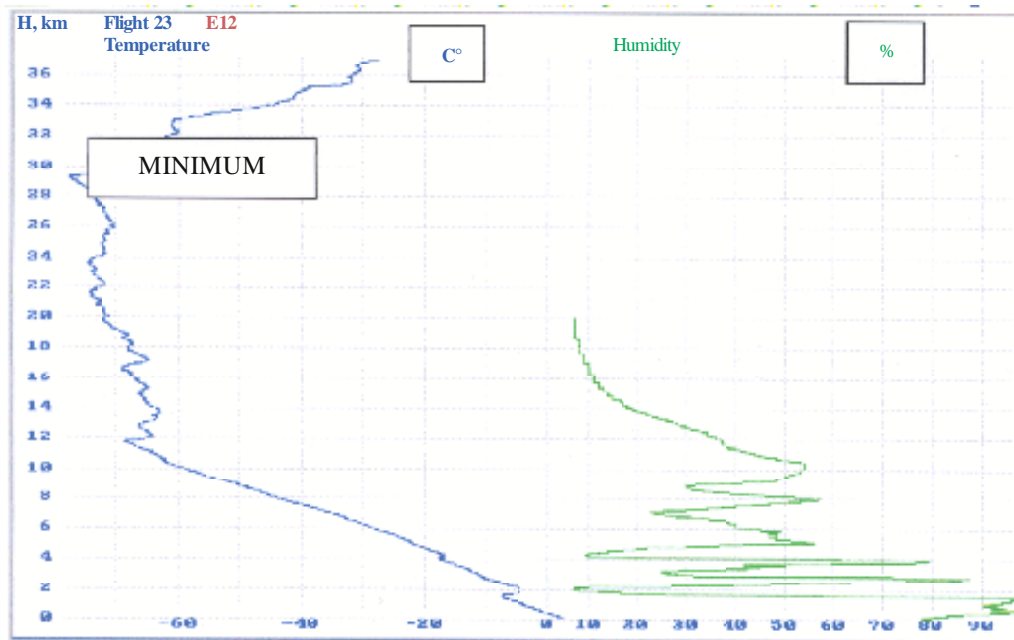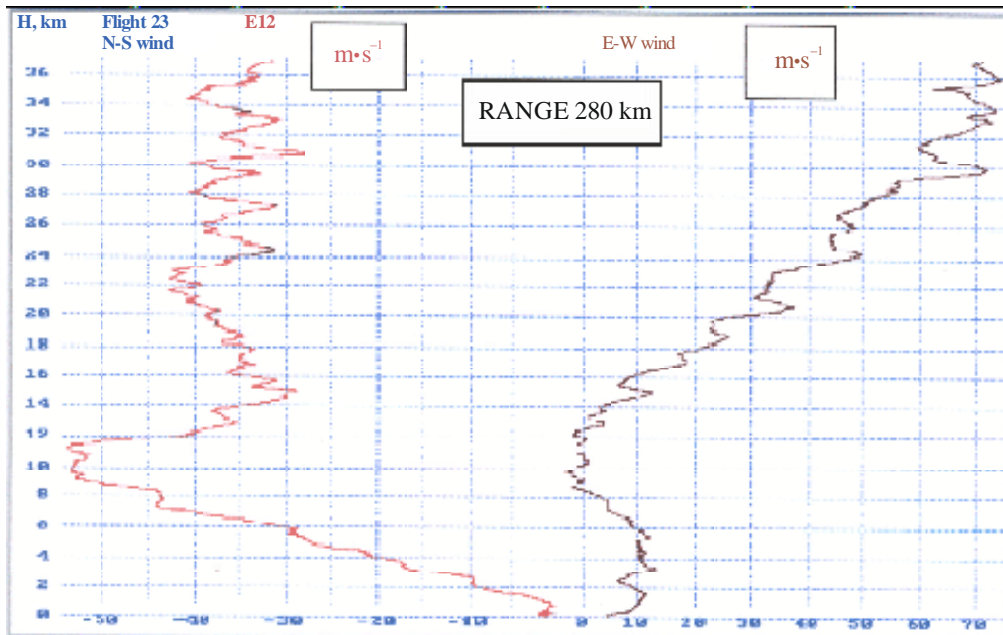

Meteo-03 -08

Due to limitations in sensor technology, the humidity measurements terminate at height of 20 km. The minimum temperature in Fig. 3-8 occurred at about 29 km [2]. The pronounced rise in the temperature above 29 km can be attributed to significant warming that takes place as a result of upper atmospheric motion during winters in the northern hemisphere.

Figure 3-9 shows wind measurements resulting from tracking the position of the same radiosonde flight (launched from Lerwick, Shetland Islands, 23 January 2000) as shown in Fig. 3-8. The movement of the radiosonde was computed using Loran-C navigation signals received by the radiosonde and then transmitted back to the base station. Accuracy is expected to be about 0.5 ms^{-1} for each of the two orthogonal components shown at short range, decreasing to about 1.5 ms^{-1} at the longest ranges, when the transmission back to the base station is less than optimal. In the N-S direction the strongest winds occurred between an altitude of 10 km and 12 km, with a jet stream centred near the temperature discontinuity at 10 km in Fig. 3-8. On this day, the E-W component was weak near the maximum of the jet stream, but the strength of this component increased uniformly at upper levels from 14 km to 30 km. This increase in winds was the result of a consistent temperature gradient from south to north, at all heights from 14 km to 30 km, with the air colder to the north nearer the centre of the polar vortex. Upper wind measurements have a high value for air transportation and defence services. The results of a MetAids observation, such as in Fig. 3-9, will usually be transformed into a special defence code at the base station and transmitted to the relevant operational units.

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[2]   At this point, the temperature had fallen close to the conditions that are needed to initiate the chemical mechanisms that destroy ozone during winters in the northern hemisphere.

FIGURE 3-9

Wind measurements by radiosonde

Meteo-03 -09

Figure 3-10 is an example of the measurements of the vertical structure of ozone from the same location in the UK as shown in Fig. 3-8. Here, partial pressure of ozone is plotted as a function of height, alongside a simultaneous measurement of temperature. The ozone measurements are made several times a week in support of ongoing scientific investigations. Measurements are transmitted immediately to a data collection hub coordinating the observations from many other sites at similar latitudes. Warnings are issued if serious depletion of ozone is happening. Ozone is usually low in the troposphere, i.e. at layers below 5 km on this day. In the stratosphere, high concentrations of ozone were found at 10 km and 20 km but not at 15 km in this case. The measurements are organized by the scientific community to identify the origin of low ozone concentrations in the stratosphere. This may be caused by the natural transport of ozone from regions with low concentrations.

FIGURE 3-10

Measurement of ozone distribution in the vertical uses an ozone sonde

LERWICK OZONE ascent 26/2/99

Meteo-03-10
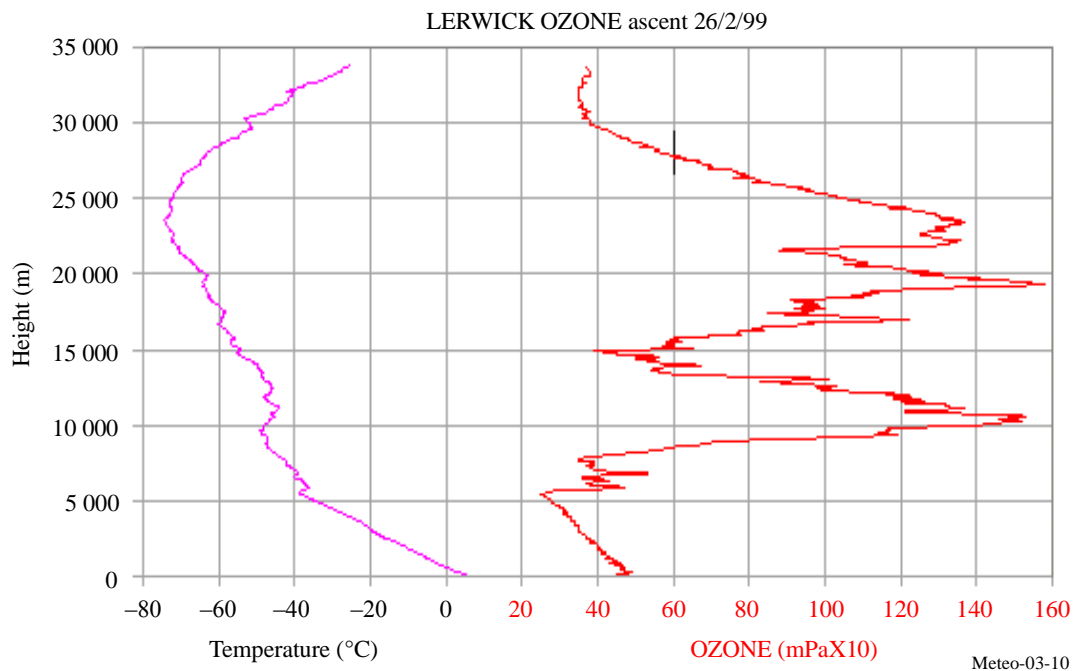
3.5 Reasons for national variations in MetAids service operations

3.5.1 Variation in available technology

While most radiosonde systems are purchased from a limited number of international commercial suppliers, economic or political conditions in some countries require that national facilities be established for radiosonde manufacture within the country. In practice, progress with the national systems has lagged the development of the radiosonde systems that have occurred with the commercial suppliers in the last two decades. Thus, while most of the technology of the commercially supplied systems used around the world is less than 5 years old, some of the national systems are still based on 30-40 year old technology. The measurements from these national systems are very important for all meteorologists, and adequate time must be allowed for these countries to introduce upgraded systems with more efficient use of the available radio frequency spectrum.

3.5.2 Differences in upper wind climatology

It can be seen in Fig. 3-9 that the balloon on this flight drifted 280 km from the point of launch before it burst and the radiosonde then descended by parachute to the surface at even longer range. To obtain reliable winds at these ranges it is essential to use radiosondes that receive a GNSS signal. Usually the balloons do not drift quite as far as this. At high latitudes in the Northern Hemisphere winter, the winds at heights above 16 km are not usually distributed symmetrically around the pole. Thus, very strong stratospheric winds are much more common over Europe than in North America. On the other hand, there are many countries where upper winds are always weak. The differences in upper wind conditions lead to significant differences between the operating conditions of the relevant national radiosonde networks. The radiosonde will always remain at high elevations and short range in some countries (e.g. in the tropics); while in others the radiosonde must be tracked down to elevations lower than 5 degrees above the horizon at ranges in excess of 200 km.

Where balloon elevations remain high (particularly if elevations lower than 15 degrees are rare), the costs of the radiosonde measurement can be reduced by using lower-cost radiosondes which do not need to receive and process a NAVAID/GNSS signal. Instead, the radiosonde can be tracked using a scanning directional antenna at the base station. If the radiosonde transmits at frequencies around 1 680 MHz, a suitable directional antenna is much smaller than the alternative antenna for frequencies near 403 MHz. The frequencies near 403 MHz are

preferred for long-range radiosonde operations for a variety of reasons, and are able to provide good reception and accurate winds throughout the ascent.

Radiosondes for 1680 MHz secondary radars may be very cheap as they may have neither a NAVAID/GNSS receiver nor a pressure sensor therefore some countries have no other alternatives to their use.

In many developed countries, the cost of employing an operator to monitor the radiosonde measurement has become too high, and the requirement for fully automated balloon launch systems, supervised from a remote site is growing, and many are now in operation. These systems always use NAVAID/GNSS radiosondes operating in the 400.15-406 MHz band. The automated system has to have a minimum of two available radiosondes, present at different operating frequencies in the band. As with manned operations, if the first radiosonde launch fails with an early balloon failure, the radiosonde may continue to transmit. In addition, another radiosonde launched from a nearby site may already be using the nominal station frequency. The automated launch system scans between 400.15 MHz and 406 MHz in advance of launch, to ensure that a radiosonde is not already transmitting within range at the selected frequency. In both situations, a second frequency must be available to obtain the operational measurement.

3.5.3   Differences in network density

The WMO has defined and regularly reviews the minimum global and regional density requirements of MetAids networks. The spectrum requirements of the MetAids service vary on a country-by-country basis dependent upon the density of the network. Any estimate of spectrum requirements must be based on the whole user community for the service including defence and environmental agencies. Higher network density requires greater spectrum efficiency. The countries that operate the more dense networks usually have the budgetary resources to procure MetAids with more spectrum-efficient transmitters. These countries are usually the countries where there is also the greatest variation in atmospheric conditions from day-to-day. Countries that operate low-density networks may not have the resources to operate a large number of stations.

3.5.4   Use of the 401-406 MHz band

Some countries in Europe operate very dense networks, using radiosondes with minimal drift and narrow-band emissions in this band. Some other countries operate broadband secondary radar systems where the ground station transmits a pulse to the radiosonde, and the radiosonde responds to the pulse and transmits the meteorological data. In both cases, nearly the full 400.15-406 MHz band is required for operations, given that between 401 MHz and 403 MHz, the MetAids service has to coordinate with the data collection platform transmissions of the EESS (Earth-to-space) and MetSat (Earth-to-space) services.

There are some areas of the world where there are a limited number of launch stations. In such cases, the resources may be available to procure transmitters that can free some of the band for other uses. Australia is one case where the full band is not required and the administration has elected to use a portion of the band for other radio communication services. Therefore, spectrum may be available in some countries for other uses, but in a number of regions of the world, the entire band is required for MetAids operations. The WMO concluded that the entire 400.15-406 MHz band is required for MetAids operation for the foreseeable future and also accepted that standard radiosonde operations in the 400.15-401 MHz band may not be possible in the future because co-channel sharing with satellite services is not feasible.

3.5.5   Use of the 1 668.4-1 700 MHz band

The situation in the 1 668.4-1 700 MHz band is different from the 401-406 MHz band. In particular, though the entire band is allocated to MetAids, the band is also allocated to the MetSat service on a co-primary basis. Co-channel MetAids and MetSat operations are not compatible and significant band segmentation has already occurred. MetAids cause significant levels of interference to the MetSat ground stations. Use of the 1 680 MHz band varies around the world, but in several parts of the world (North America, Europe and Asia), only the 1 675-1 683 MHz sub-band may be available for MetAids operations. In discussing MetAids requirements in 1 668.4-1 700 MHz, it must be kept in mind that only a portion of the band is usually available. Most countries can conduct operations in 7-8 MHz of spectrum, while there are a number of countries where upwards of 15 MHz is still required to support operations.

3.5.6   Requirements for the retention of both bands

The availability of both RF bands to MetAids operations is judged critical for continued successful meteorological operations. First, in a number of countries in Europe and North America, both bands are necessary to fill the spectrum requirements of MetAids operations, given the existing sharing arrangements with other services. Synoptic, research, and defence MetAids operations cannot be satisfied with the availability of just one of these bands. In addition, each band provides unique characteristics required for different types of MetAids operations. The band 401-406 MHz offers a lower propagation loss. This propagation loss provides advantage in parts of the world where high winds result in long slant ranges between the base station and the radiosonde. The lower propagation loss also allows use of simpler, smaller receive antennas for tracking the flight. MetAids operations in this band use a form of radio navigation (GNSS) for measurement of winds since a RDF antenna would be prohibitively large. For either budgetary and/or national security reasons, some administrations choose to use the band 1 668.4-1 700 MHz. For this band, RDF MetAids eliminate the need for radio navigation circuitry. This reduces the cost of the expendable devices. Some countries operate their MetAids systems that are independent of international NAVAID/GNSS systems as such, these systems may not always be available.

3.6   Future trends

While MetAids designs are typically very simple and use low cost components, evolution has occurred and will continue to occur to improve the performance of the systems. As previously noted, many of the investments for improvement are for the sensor qualities and not always on the telemetry link portion of the system. However, the increasing requirement for additional frequency assignments in a given area to support both synoptic and non-synoptic operations has demonstrated improvements in the RF characteristics as well.

In addition, implementation of GNSS on radiosondes for purposes of measuring winds has already led to significant improvements in the spectrum efficiency of NAVAID/GNSS radiosondes. In most countries, it also allows a significant improvement in the accuracy of upper wind and height measurements. The availability of small low-cost GNSS receivers now allows that the GNSS signal is completely processed onboard the MetAids and that only wind and position data are transmitted. There is currently no more need for many applications to transmit "differential" GNSS data to recover the quality of the GNSS data; and this reduces the amount of data that need to be transmitted.

CHAPTER 4

METEOROLOGICAL RADARS

4.1   Introduction

Ground-based meteorological radars operate under the radiolocation service and are used for operational meteorology, weather prediction, atmospheric research and aeronautical and maritime navigation. Most weather are in operation continuously 24 h/day and play a crucial role in the immediate meteorological and hydrological alert processes. These radars represent the last line of defence against loss of life and property in flash flood or severe storms events and as such are among the best-known life savers in meteorology.

Meteorological radars are typically volume scanning, pencil beam radars which detect and measure both hydrometeor intensities and wind velocities. They are used to predict the formation of hurricanes, tornadoes and other severe weather events and to follow the course of storms on their destructive paths. Modern radars permit the tracking of large and small storms and provide information on precipitation rates, which is used by forecasters in predicting the potential for flash floods. In addition, they provide relevant information on high winds and lightning potential. Meteorological radars are also a prime interest in aeronautical weather service in particular for detection of aircraft icing conditions and avoidance of severe weather for navigation.

This Chapter discusses ground-based radars commonly used in meteorology and their specificities compared to other radars.

4.1.1   Meteorological radar types

The first and most familiar of the radar types is the weather radar. These radars provide data within a volume which is centred on its own location. Familiar to many, the output of these radars is commonly shown in television weather forecasts. Table 4-1 provides the listing of frequency bands which are commonly used for weather radars operations.

TABLE 4-1

Main weather radars frequency bands

Frequency band (MHz)	Band name commonly used in meteorological community
2 700-2 900	S-Band
5 250-5 725 (mainly 5 600-5 650 MHz)	C-Band
9 300-9 500	X-Band

Wind profiler radar (WPR) is a second type of meteorological radar. These radars provide wind velocity data within a roughly cone-shaped volume which is directly above the radar. If properly equipped, e.g. with speaker units or a RASS (Radio Acoustic Sounding System) system, a WPR can also measure atmospheric virtual temperature as a function of height). The radio frequency bands used by the WPR are typically located around 50 MHz, 400 MHz, 1 000 MHz and 1 300 MHz (see details in § 4.3).

A third, less common type, is auxiliary radar which is used to track radiosondes in flight. The use of such radars is discussed in Chapter 3, which deals with radiosondes.

A fourth radar type used in meteorology is cloud radars. These radars operate normally around 35 GHz and 94 GHz because of relatively low atmospheric attenuation. Cloud radars are used for studying microphysical properties of clouds and other particles within the sensitivity range of the radar system.

All radars operate by emitting radio signals, which are reflected from a target such as vehicles, planes, raindrops or turbulence in the atmosphere. Although emitting powerful signals, the return signal of radars is weak. This is because the radiated signal must traverse the path twice, once from the radar to the target and back to the radar, leading to atmospheric attenuation on both paths. In the case of meteorological radars, this weakness is even exacerbated since the meteorological targets (being either precipitations drops (rain, hail, snow, …) or even in case of Doppler mode, dust, insects or solely atmospheric disturbances) is not a

particularly efficient reflector. The amount of signal returned is related to target reflectivity and can vary depending on the size and nature of the target. The need to receive these weak signals can be met variously by, e.g. higher transmitter powers, large antennas exhibiting high gain beamwidth product, extremely sensitive receivers, and long signal integration times. Relatively "quiet" spectrum – absence of man-made electronic noise and interference – is therefore a critical requirement.

4.1.2   Radar equation

The radar equation (4-1) describes the relationship between the returned power and the characteristics of the radar and the target. The equation can be expressed as follows:

$$\overline{P_r} = \frac{\pi^3 \cdot P_t \cdot G^2 \cdot \theta^2 \cdot c \cdot \tau \cdot \left|K\right|^2 \cdot L \cdot Z}{2^{10} \cdot \lambda^2 \cdot R^2 \cdot \ln 2}$$

(4-1)

where:

$\overline{P_r}$:   average return power (W)

P_t :   transmitter output power (W)

G :   antenna gain (dimensionless)

K :   complex index of refraction (dimensionless)

λ :   radar wavelength (m)

c :   speed of light (m/s)

θ :   antenna half power (3 dB) beamwidth (rad)

τ :   pulse width

r :   range to target

L :   loss factors associated with propagation and receiver detection (dB)

Z :   effective radar reflectivity (m^3).

Re-arranging terms results in an easy-to-understand formulation of the radar equation (4-2) which shows the different contributions to the received power in terms of constants, radar and target factors.

$$\overline{P_r} = \underbrace{\frac{\pi^3 c}{1\,024 \cdot \ln 2}}_{\text{Constants}} \cdot \underbrace{\frac{P_t \cdot G^2 \cdot \theta^2 \cdot L}{\lambda^2}}_{\text{Radar factors}} \cdot \underbrace{\left|K^2\right| \frac{Z}{R^2}}_{\text{Target factors}}$$

(4-2)

Equation (4-2) can be applied to a distributed target when the following assumptions are satisfied:

–   the target occupies the entire volume of the pulse

–   the particles are spread throughout the contributing region

–   the precipitation particles are homogeneous dielectric spheres with diameters small compared to the radar wavelength

–   the size of the particles satisfies the Rayleigh Scattering condition

–   the dielectric constant $|K|^2$ and the size distribution of the scatterers are homogeneous in the volume *V* considered

–   the antenna pattern can be approximated by a Gaussian shape

–   the incident and back-scattered waves are linearly polarized

–   the effects of multiple scattering are neglected.

A logarithmic form of the radar equation (4-2) [Doviak and Zrnic, 1984] is given in equation (4-3):

$$Z(\text{Az, El, } R)\,(\text{dBZ}) = 10\log(P_r) + 20\log(R) - 10\log(L_p) + 10\log(C) \qquad (4\text{-}3)$$

This equation is the most useful in that it illustrates the need to have clearly identified various system parameters in order to make a calibrated reflectivity measurement. These parameters include:

− received power P_r (W),

− range R (m),

− azimuth and elevation angles (degrees),

− excess propagation loss L_p (dB), and

− so-called radar constant C.

The radar constant typically includes factors such as the antenna beam width, the pulse width, the receiver conversion gain and system losses.

It must be stressed that for radars tracking discrete targets the radar equation provides a received signal which is proportional to $1/r^4$ (r being the distance). For meteorological radars, the situation is quite different since targets such as precipitations often fill the entire narrow radar beam. In this case the radar equation provides a received signal which is proportional to $1/r^2$. As a result, meteorological radars allow for larger detection ranges but this also means that they have a higher sensitivity to interference than a typical air traffic control type radar.

4.2   Weather radars

4.2.1   User requirements

Meteorologists use weather radar to detect, locate, and measure the amount of precipitation within or falling from clouds and to determine wind velocities and direction using the movement of the precipitation or atmospheric particles. The radars measure the intensity of precipitation over specific time periods as well as the movement of precipitation or atmospheric particles toward or away from the weather radar antenna, enabling the measurement of rotation within meteorological events. This is a critical factor in detecting severe weather such as tornados or flash floods and in providing advance warning. The main user requirement for the weather radar is to detect solid and liquid precipitation and estimate the rate of precipitation and the radial velocity[4].

4.2.2   Weather radar networks

The main limitation of a weather radar is the fact that the intensity of the echoes that are returned from a given meteorological event tend to decrease with increasing distance from the radar. This is not only due to free-space and other atmospheric attenuations but also to the fact that, as distance from the radar increases, the radar beam becomes higher above the ground (this is due to the Earth's curvature and the elevation angle of the beam) and also the beam broadens. (See Fig. 4-1.)

This results in a decrease in the percentage of the meteorological event that is illuminated by the beam. While the upper portion of the event can still be seen by the radar, its lower parts may no longer be visible. Precipitation that is taking place at some distance away from the radar may remain undetected or may show up with a reduced intensity thereby limiting the quantitative operational range of the radar.

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[4] This is the velocity of the precipitation either toward or away from the radar (in a radial direction). No information about the strength of the precipitation is given. Precipitation moving toward the radar has negative velocity Precipitation moving away from the radar has positive velocity. Precipitation moving perpendicular to the radar beam (in a circle around the radar) will have a radial velocity of zero.

FIGURE 4-1

Synthetic description of radar beam height increase with distance
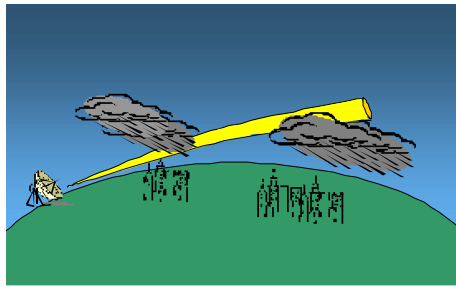
Meteo-04-0 1

To overcome this constraint, multiple radars are generally equally spaced into distributed networks. These networks operate 24 hours per day and cover, in general, large areas such as countries or even a portion of a continent in order to detect and follow the evolution of meteorological phenomena, therefore permitting early weather hazard warnings. One such network, comprising S-Band, C-Band and X-Band radars, as deployed in Western Europe, is given on Fig. 4-2.

FIGURE 4-2

Example of a weather radar network
(update March 2016)
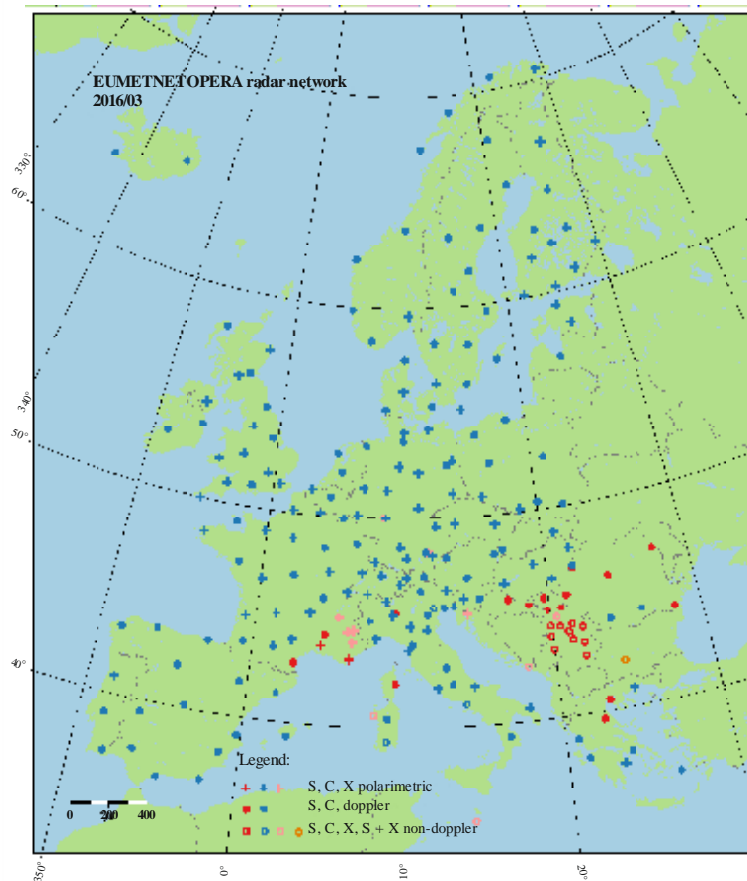
Meteo-04-02

4.2.3   Operational aspects of reflectivity

Reflectivity is a radar term referring to the ability of a radar target to return energy. The reflectivity η of rain is related to the water relative permittivity ε_r, the drop diameter D, and the wavelength λ. For raindrops contained within the volume V under consideration, the reflectivity can be expressed as equation (4-4):

$$\eta = \frac{\pi^5}{\lambda^4} |K|^2 \sum_j D_j^6 / V \qquad\qquad \mathrm{m}^{-1} \qquad\qquad (4\text{-}4)$$

where $|K|^2$ is 0.93 for liquid water and 0.18 for ice. Reflectivity is used to estimate precipitation intensity and rainfall rates and is a measure of the returned power.

For precipitation events where the raindrop size is known (or assumed), volume reflectivity can be related to the total liquid water volume per unit volume. The total volume of water in conjunction with the drop-size distribution and the corresponding terminal velocity of the drop facilitate the calculation of rainfall rate.

The radar reflectivity factor Z can be defined as:

$$Z = \frac{1}{V_e} \sum_i D_i^6 \qquad\qquad (4\text{-}5)$$

where:

Z: volume that is implied from the scatterer radar cross section of the total number of spheres in the volume

D: water drop diameter

V_e: effective drop volume.

The volume Z is related to the radar cross section per unit volume η by:

$$\eta = \frac{\pi^5}{\lambda^4} |K|^2 Z \qquad\qquad (4\text{-}6)$$

where:

Z: volume

η: radar cross section per unit volume

λ: incident wavelength

$|K|$: complex index of refraction.

Since the diameter of raindrops within the scattering volume is not uniform, the raindrop distributions can be approximated by:

$$N(D) = N_0 \exp(-\Lambda D) \qquad\qquad (4\text{-}7)$$

where:

$N(D)$: number concentration of the diameter

D: diameter

ΛD: size interval

N_0 and Λ: constants for a given meteorological event.

When the raindrop size distribution is known, the summation $\sum_i D_i^6$ over a unit volume is given by:

$$Z = \int_0^\infty D^6 N(D)\,\mathrm{d}D \qquad\qquad (4\text{-}8)$$

When the vertical airspeed is zero the rainfall rate, R, is given by:

$$R = \frac{\pi \rho}{6} \int_0^\infty D^3 v_t(D) N(D) \, dD \tag{4-9}$$

where:

R: rainfall rate

D^3: raindrop volume that is proportional to Z

$v_t(D)$: terminal velocity of a raindrop having a diameter D

ρ: density of water.

When N_0 is constant the implied *Z-R* relationship can be described by equation (4-10):

$$Z = AR^b \tag{4-10}$$

Where Z is usually expressed as $dB_Z = 10 \log Z$ (mm^6/m^3) and A and b are constants. (A is the scattering constant and b is the rate multiplier.) The most commonly used *Z-R* relationship is the Marshall-Palmer where: $Z = 200 \cdot R^{1.6}$ Z and R are expressed in mm^6/mm^3 and in mm/h, respectively. The *Z-R* relationship is however, not unique. Both A and b depend upon the drop size distribution (DSD) which varies with the type and intensity of rain.

4.2.4   Weather radars emission schemes, scanning strategies and operational modes

4.2.4.1 Emission schemes

To ensure volume scan processing, in so-called "scanning strategies" (typically in a range of 5-15 min), meteorological radars make use of a variety of different emission schemes at different elevations, using sets of different pulse width, PRF's and rotation speeds. There is not one 'typical' scheme, the schemes varying depending on a number of factors such as the radar capabilities and the radar environment for the required meteorological products. The schemes are hence tuned to best meet the requirements.

As an example, a recent enquiry on C-Band meteorological radars showed following large ranges of different emission scheme parameters:

–   Operational elevation ranging from 0° to 90°

         Pulse width ranging from 0.5 to 3.3 µs (for operational radars) for uncompressed pulses, whereas some radars use pulse compression with pulse width ranging from 30 µs to 350 µs (noting that use of pulse compression increases the required bandwidth (3 to 6 MHz))

–   Pulse repetition Frequency (PRF) ranging from 250 to 2 400 Hz (for operational radars). Some existing radars are capable of PRF up to 20 000 Hz

–   Rotation speed ranging from 1 to 10 rpm

–   Use on a given radar of different emission schemes mixing different pulse widths and PRF's, and in particular the use of fixed, staggered or interleaved PRF (i.e. different PRF during a single scheme).

Example of different emission schemes are provided on Fig. 4-3.

FIGURE 4-3

Some types of weather radar emission schemes
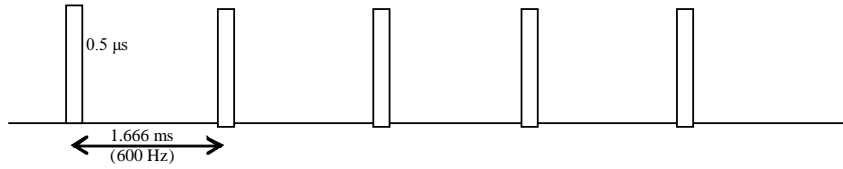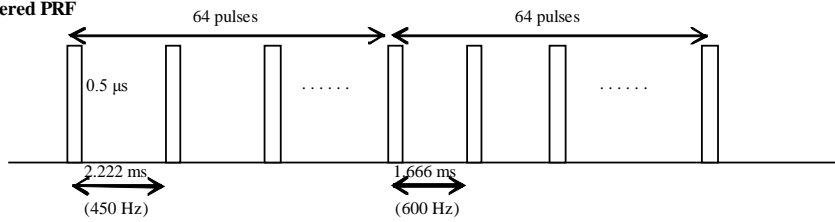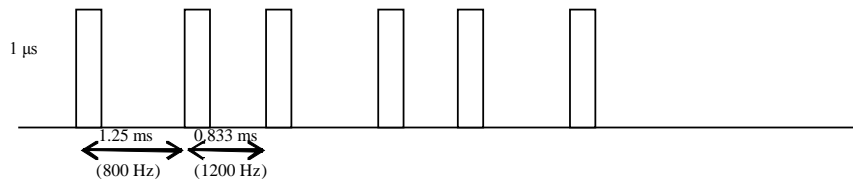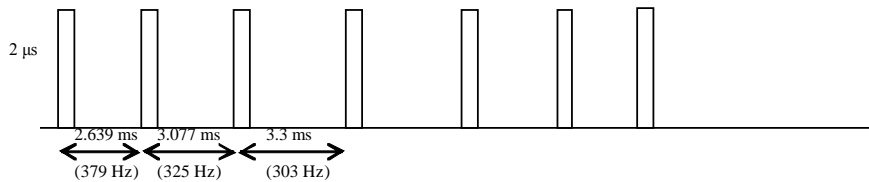
Meteo-04-03

These different emission schemes are used on a number of radars in their scanning strategy, during which, at different elevations and rotation speeds, one emission scheme is transmitted.

It has to be stressed that, from one radar to another, the PRF and pulse width values associated with these example schemes vary within the ranges defined above. In addition, for a given scheme, pulse widths can vary on a pulse to pulse basis.

Below is an example of such scanning strategy:

FIGURE 4-4

Description of a weather radar scanning strategy

Typical scan strategy (total time around 15 min):

- 1 round at elevation 0.8° with configuration 2 (2 rpm) (30 s)
- 1 round at elevation 10° for noise calibration (3 rpm) (20 s)
- 12 rounds at elevations 37, 29, 23, 21, 19, 17, 15, 13, 11, 9.5, 8.5 and 6.5° with configuration 3 (3.167 rpm) (19 s/turn) (3 min 47 s total)
- 1 round at elevation 0.8° with configuration 2 (2 rpm) (0.5 min)
- 2 rounds at elevations 6.5 and 5.5° with configuration 3 (3.167 rpm) (19 s/turn) (38 s total)
- 5 rounds at elevations 4.5, 3.5, 2.5, 1.5 and 0.5° with configuration 3 (3 rpm) (20 s/turn) (40 s total)
- 4 rounds at elevations 0.5, 1.5, 2.5 and 3.5° with configuration 1 (2 rpm) (2 min)
- 1 round at elevation 0.8° with configuration 2 (2 rpm) (30 s)
- 2 rounds at elevations 3.5 and 4.5° with configuration 1 (2 rpm) (60 s)
- 1 round at elevation 10.5° with configuration 3 (3 rpm) (20 s)
- 1 round at elevation 1.3° with configuration 2 (3 rpm) (20 s)
- 1 round at elevation 0.8° with configuration 2 (2 rpm) (30 s)
- 1 round at elevation 10° for noise calibration (3 rpm) (20 s)

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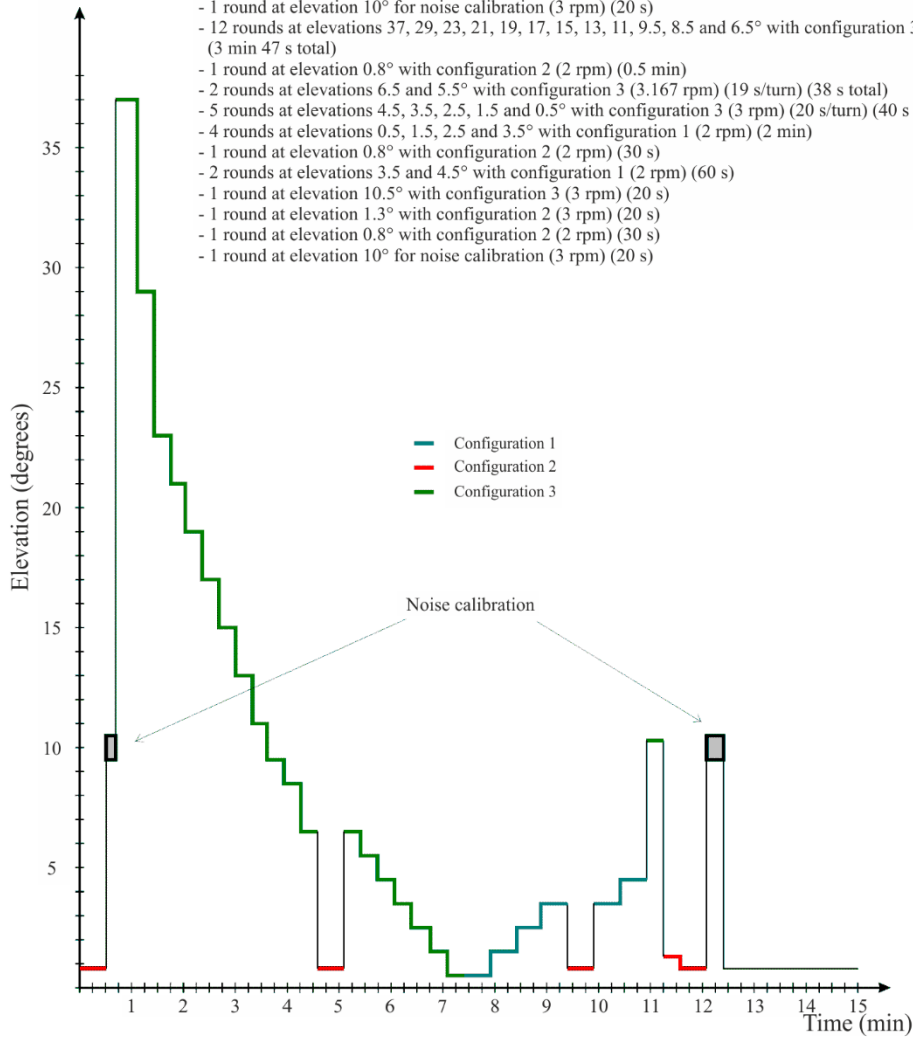
FIGURE 4-5

Emission schemes associated with scanning strategy as in Fig. 4-4
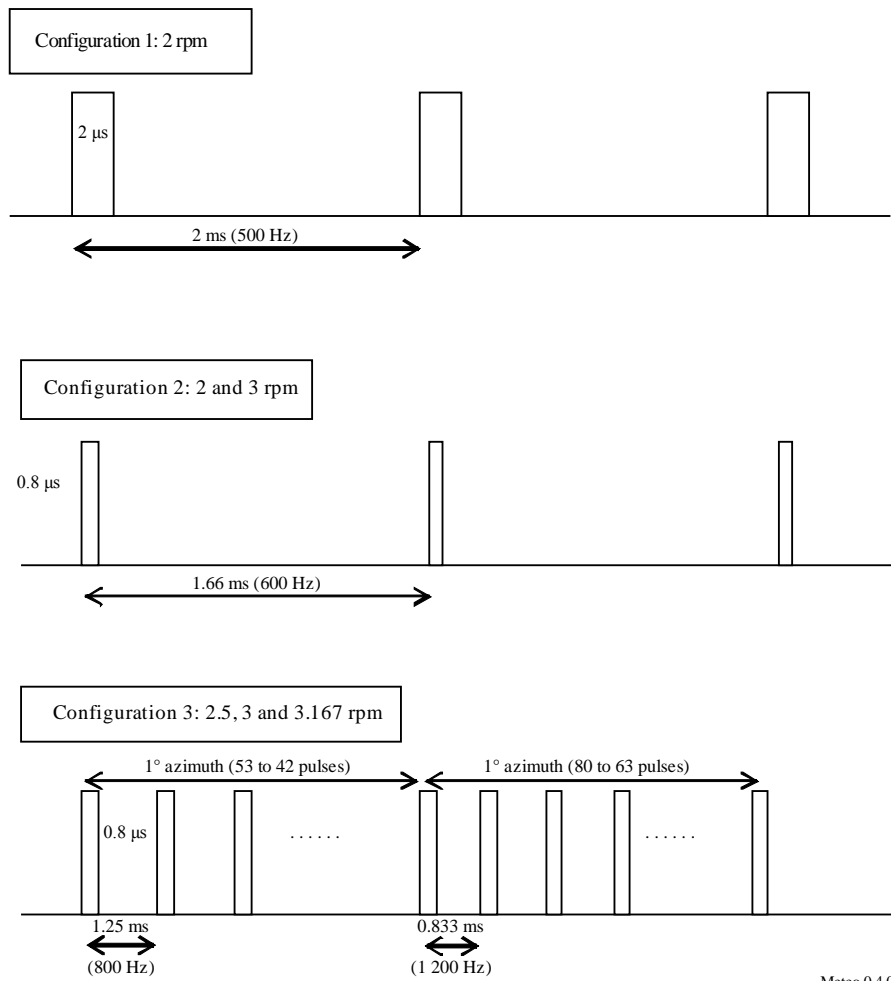
4.2.4.2 Noise calibration

Considering the weakness of the return signal to meteorological radars, the noise level has to be extracted from the signal in order to achieve the most accurate measurements and retrieve relevant meteorological products.

Noting N, the noise level and S the useful signal (i.e. meteorological signal return), meteorological radars perform the following process:

1   for each gate, the radar measures the return signal corresponding to the useful signal (S) and the noise (N), i.e. $N + S$

2   To get the S, the radar extract from $N + S$, the noise level N

3   Then, from the S, the radar is able to determine all meteorological products, such as the precipitation (dB$_Z$) or wind velocity by Doppler analysis.

In order to get the more precise meteorological products, the signal S has to be as accurate as possible which means that the noise calibration, also called "Zero check", of the radar is a crucial issue.

"Zero check" is therefore performed on a regular basis, either during regular radar emissions (by estimation) or during specific measurement periods of time (see the example scanning strategy below) during which the noise is measured.

In many cases, this noise measurement is performed without any radar emission (this could in particular have an impact on the design of certain radio systems that aim at detecting radar signal to mitigate interference).

In all cases, interference received during the noise calibration will corrupt all data collection until the next interference free calibration is performed. Such interference could lead to presenting lower precipitation rates than the real situation, with obvious consequences on operational and alert processes.

4.2.4.3 Operational modes for meteorological radar

Radars in some networks, e.g. NEXRAD in USA, operates in two user selectable modes: Clear air mode and precipitation mode. Clear air mode requires manual selection by the user. The precipitation mode may be selected manually at any time during operation or can be automatically operated whenever the weather radar detects precipitation (based upon pre-determined values and area coverage of reflectivity).

In general, meteorological radars take advantage of both modes.

4.2.4.3.1 Clear air mode

Clear air mode provides meteorological radars the ability to detect early signs of precipitation activity.

There exist certain variables in low-level velocity and air density that allow for detection of potential precipitation. The radar utilizes a slow scan rate, coupled with a low PRF, to employ a high sensitivity capability. This high sensitivity is ideal for very subtle changes in atmospheric conditions at long ranges. The clear air mode is especially useful when there is little to no convective activity within the transmit range of the radar, and is ideally suited for detecting the signs of developing thunderstorms or other types of severe weather.

Meteorological radar's high sensitivity is due to the volume scan pattern within the clear air mode. By selecting a pattern in the clear air mode; the radar antenna is capable of dwelling for an extended period in any given volume of space and receives multiple returns, while allowing operation at a lower S/N. The use of a wide pulse width and a low PRF provides approximately 8 dB echo power for a given dBz of reflectivity.

4.2.4.3.2 Precipitation mode

The precipitation mode performs a distinctly different purpose than the clear air mode. The scan rate for the precipitation mode is a function of the elevation angle. This dependence allows for the highest number of elevation angles possible in sampling the total radar volume. The precipitation mode takes advantage of multiple volume coverage patterns (VCPs) to implement different types of scan strategies (see example in § 4.2) with different elevation sampling. Weather events normally monitored in the precipitation mode are associated with the development of precipitation involving convective storms (rain showers, hail, severe thunderstorms, tornadoes, etc.) and large-scale synoptic systems.

4.2.4.4 Fixed echo elimination

The so-called fixed echo includes several hidden fixed components; one that includes low frequency scattering, and a second that includes higher frequencies (e.g. due to vegetation ruffled by the wind). Echoes due to non-precipitation targets are known as clutter, and should be eliminated. Different ground clutter suppression methods are used in current weather radars:

–   Doppler filtering uses a high pass filter to reduce the ground clutter. That process is efficient if the radial wind velocity is above the cut-off frequency of the Doppler filter.

–   Statistical filtering based on the fact that the variance of rain is higher that the variance of ground clutter reflectivity. The statistical filtering process is efficient even when the rain radial velocity is null (tangential rain).

–   The use of polarimetric radar for rain and ground clutter discrimination.

4.2.5 Doppler radars

Doppler weather radars have been used for more than 30 years in atmospheric research to measure convection within thunderstorms and to detect gust fronts and are now widely used for operational weather radar systems. Unlike earlier radars, Doppler equipment is capable not only of determining the existence and position of

reflective targets but also their radial velocity. This permits the measurement of wind speed, detection of tornadoes, and the measurement of a wind field using velocity azimuth display scanning.

Ground clutter suppression is an important capability. New developments in this area are focused on coherent transmitters such as klystrons (that are state-of-the-art nowadays), traveling wave tubes (TWTs) or Solid State. Conventional radar spectrum phase purity was limited by previous generation magnetron technology, but in modern magnetrons the phase purity is sufficient for effective clutter cancellation. However, the existing magnetrons can economically deliver high average power to increase the signal to noise ratio.

4.2.6   Dual-polarization radars

Polarimetric or dual-polarization radars transmit pulses in both horizontal (h) and vertical (v) polarizations. This technology permits the identification of scatterers by remotely sensing their shapes and homogeneity. These radars provide significant improvements in rainfall estimation, precipitation classification, data quality and weather hazard detection over non-polarimetric systems.

Precipitation estimations now make use of the fact that falling raindrops tend to flatten (oblate spheroids), the flatness increasing with drop size in the horizontal direction. Combining reflectivity and dual-polarization fields, enables a better assessment of the coefficients A and b of the Z-R relationship (4-10). Other algorithms, based on differential phase $\varphi_h - \varphi_v$ and differential attenuation, are considered very promising for further improving accurate assessments of rainfall.

In addition to their shape, the hydrometeors are characterized by their dielectric constants, a primary factor in computing scattering and attenuation cross sections. Dielectric properties of hydrometeors vary with radar frequency, where liquid water and ice differ significantly. Taking advantage of these characteristics, algorithms have been implemented to discriminate between rain and snow and to quantify liquid water and ice in clouds using differential attenuation measurements.

4.2.7   Conventional meteorological radar base data products

A Doppler meteorological radar generates three categories of base data products from the signal returns: base reflectivity, mean radial velocity, and spectrum width. All higher-level products are generated from these three base products. The base product accuracy is often specified as a primary performance requirement for radar design. Without the required accuracy at this low level, as given in Table 4-2, the higher-level derived product accuracy cannot be achieved.

TABLE 4-2

Representative met radar base data accuracy requirements

Base data product	Design accuracy requirement
Base reflectivity	< 1 dB
Mean radial velocity	< 1 m/s
Spectrum width	< 1 m/s

4.2.7.1 Base reflectivity

Base reflectivity is used in multiple weather radar applications, the most important of which is rainfall rate estimation. Base reflectivity is the intensity of the return pulses and is calculated from a linear average of return power. Any interference to the radar adds to the return pulse power and biases the reflectivity values. Reflectivity measurements can be compromised if the bias exceeds the base data accuracy requirements.

FIGURE 4-6

Reflectivity from KOUN at 22:34 UTC on 2011/05/24 during a tornado outbreak
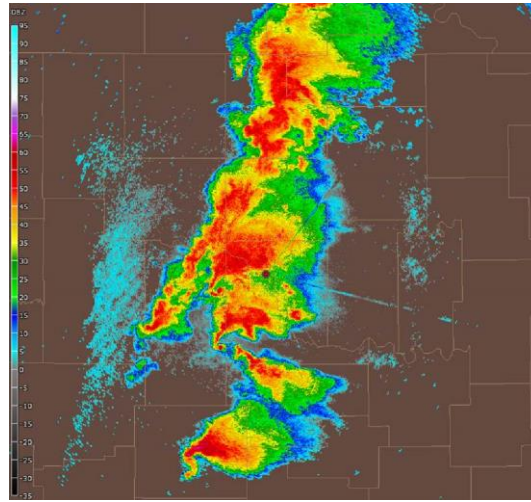
Meteo-0 4-06

4.2.7.2 Mean radial velocity

Mean radial velocity is also known as the mean Doppler velocity, and represents the reflectivity weighted average velocity of targets within a given volume sample. Mean radial velocity refers to the spectral density first moment; radial velocity to the base data. It is usually determined from a large number of successive pulses and is calculated from the argument of the single lag complex variance. The complex covariance argument provides an estimate of the Doppler signal vector angular displacement from radar pulse to radar pulse. The Doppler vector angular velocity is equal to the displacement divided by the time interval between pulses. The Doppler spectrum reveals the reflectivity and radar weighting distribution of velocities within the radar volume.

FIGURE 4-7

Radial velocity from KOUN at 22:34 UTC on 2011/05/24 during a tornado outbreak
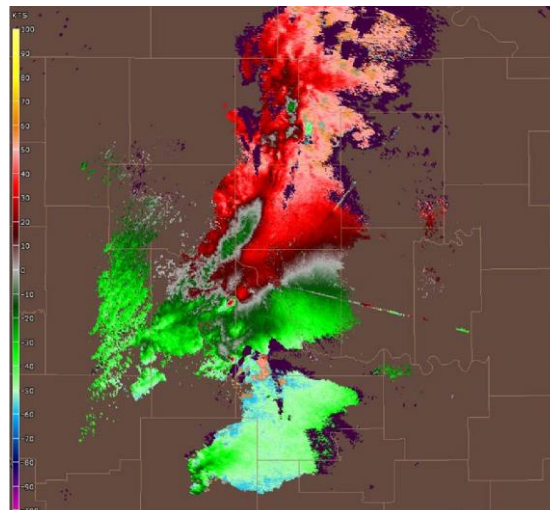
Meteo-04-07

4.2.7.3 Spectrum width

In meteorological radar design, spectrum width is calculated from the single lag correlation assuming a Gaussian spectral density. It is a measure of the dispersion of velocities within the radar sample volume and is the standard deviation of the velocity spectrum. Spectrum width depends on reflectivity and velocity gradients across the pulse volume and turbulence within the pulse volume [Doviak and Zrnic 1984].

FIGURE 4-8
Spectrum width from KOUN at 22:34 UTC on 2011/05/24 during a tornado outbreak
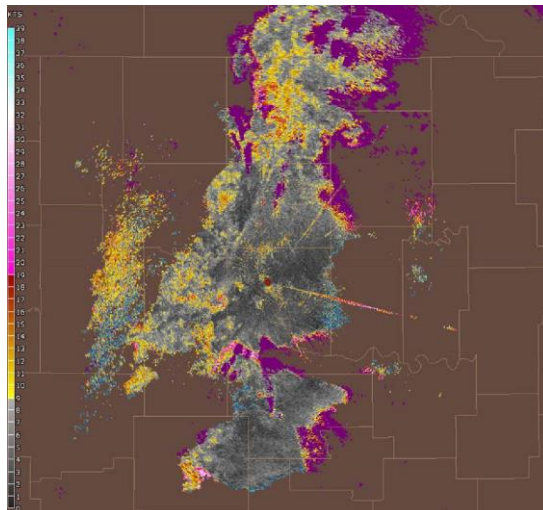
Meteo-0 4-08

4.2.7.4 Dual polarization meteorological radar products

4.2.7.4.1 Differential reflectivity

Differential reflectivity is a product that is associated with polarimetric meteorological radars, and is a ratio of the reflected horizontal and vertical power returns. Among other things, it is a good indicator of particle shape. In turn the shape is a good estimate of average particle size.

FIGURE 4-9
Differential reflectivity from KOUN at 22:34 UTC on 2011/05/24 during a tornado outbreak
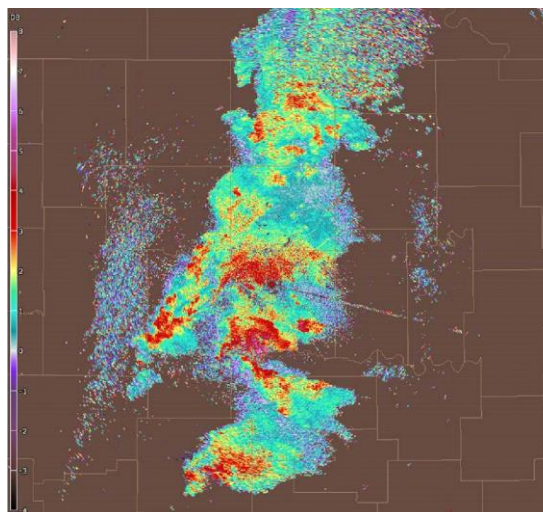
Meteo-0 4-09

4.2.7.4.2 Correlation coefficient

Correlation coefficient is a polarimetric meteorological radar product and is a statistical correlation between the reflected horizontal and vertical power returns. The Correlation coefficient describes the similarities in the backscatter characteristics of the horizontally and vertically polarized echoes. It is a good indicator of regions where there is a mixture of precipitation types, such as rain and snow.

FIGURE 4-10

Correlation coefficient from KOUN at 22:34 UTC on 2011/05/24 during a tornado outbreak
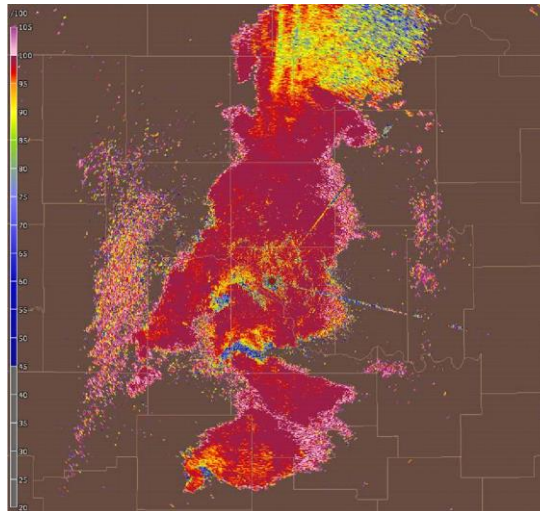
Meteo-0 4-10

4.2.7.4.3 Linear depolarization ratio

Another polarimetric radar product is linear depolarization ratio which is a ratio of a vertical power return from a horizontal transmitted pulse or a horizontal power return from a vertical pulse (not shown). Similar to correlation coefficient, it is a good indicator of regions where mixtures of precipitation types occur.

4.2.7.4.4 Differential phase

The differential phase is a comparison of the returned phase difference between the horizontal and vertical pulses. This phase difference is caused by the difference in the number of wave cycles (or wavelengths) along the propagation path for horizontal and vertically polarized waves. It should not be confused with the Doppler frequency shift, which is caused by the motion of the cloud and precipitation particles. Unlike the differential reflectivity, correlation coefficient, and linear depolarization ratio, which are all dependent on reflected power, the differential phase is a "propagation effect". It is also a very good estimator of rain rate and attenuation caused by rain. Specific differential phase (not shown), derived from differential phase, shows the rate at which the phase is shifting. This is especially useful for identifying regions of heavy rain.

FIGURE 4-11

Differential phase from KOUN at 22:34 UTC on 2011/05/24 during a tornado outbreak
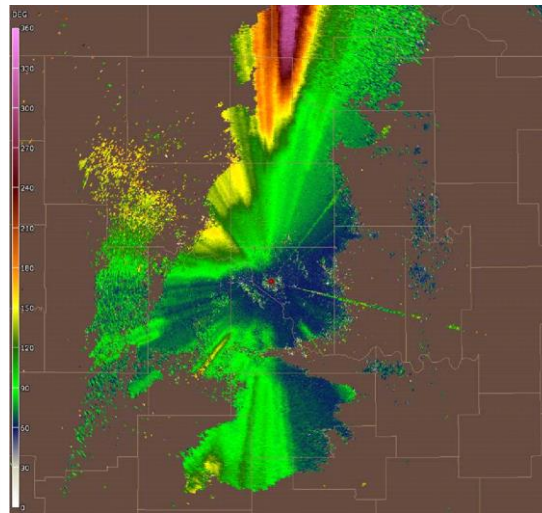
Meteo-0 4-11

4.2.7.5 Derived data products

Using the base data products, the processor produces higher-level derived data products for the radar user. This document will not address the derived data products in detail as the products vary from radar to radar and the number of products is quite large. To ensure accuracy of the derived data products, the base data products need to be accurately maintained.

4.2.8   Antenna pattern and antenna dynamics

4.2.8.1 Antenna patterns

Meteorological radars typically use parabolic reflector antennas that produce a pencil beam antenna pattern. Antenna dynamics in the horizontal and vertical planes are considered to produce a volume scan. Example of such dynamics is described in § 4.2.4.1 above.

Three mathematical models for meteorological radar antenna patterns are currently used as given in Recommendations ITU-R F.699 (peak side lobes), ITU-R F.1245 (average side lobes) and ITU-R M.1652. Although representative of parabolic antennas, these Recommendations tend to slightly overestimate the beamwidth of a pencil beam antenna pattern.

It is noted that currently there are no defined radar antenna radiation pattern equations within ITU-R to represent such pencil beam antennas.

4.2.8.2 Volume scan antenna movement

The horizontal and vertical coverage required for a volume scan to produce a horizontal cut, is achieved by rotating the antenna in the horizontal plane at a constant elevation angle. The antenna elevation is increased by a pre-set amount after each horizontal cut. The lowest elevation angle is typically in the range of −2º to 1º, and the highest elevation is in the 20º to 30º range, though some applications can use elevations up to 60º. Rotation speed of the antenna varies depending on weather conditions and the product required at the time. The rotation speed as well as range of elevation, intermediate elevation steps, and pulse repetition frequency, is adjusted for optimum performance. Slow antenna rotation provides a long per-radial dwell time for maximum sensitivity.

High antenna rotation speed allows the operator to generate a volume scan in a short period of time when it is desirable to cover the entire volume as quickly as possible. Variation of the elevation steps and rotation speed can result in volume scan acquisition times ranging from one minute up to 15 min. The long periods of time

for a complete volume scan, compared to other radars that rotate at a constant elevation, is explained by the necessity to obtain a statistically significant sampling of results.

4.2.8.3 Other antenna movement strategies

Meteorological radars also use other antenna movement strategies for special applications and research. Sector scans are used to get part of an elevation cut. Sector volume scans perform a volume scan for a fraction of the 360° azimuth where the antenna takes multiple elevations cuts. The third mode holds the antenna at a constant azimuth and elevation to monitor a specific point in the atmosphere. All three strategies allow the radar operator to concentrate on a specific part of the atmosphere.

4.2.9   Present and future spectrum requirements

As for a number of radar applications, the choice of the frequency band (or wavelength λ) mainly results from a trade-off between the range/reflectivity, which varies as λ^{-4}, the rain attenuation, meteorological variable accuracy, and cost. Attenuation in precipitation, which decreases as λ increases to become negligible at wavelengths in the decimetre range, is a dominant consideration. For example, the Ka band (around 35 GHz, 8.6 mm wavelength) is well suited for detecting small water drops, which occur in non-precipitating clouds (≤ 200 μm) whereas, on the other hand, the S-band (2700-2900 MHz, 10 cm wavelength) is chosen for detecting heavy rain at very long ranges (up to 300 km) in tropical and temperate climates.

4.2.9.1 Weather radar frequency bands

The three bands most commonly employed in meteorological radars are S-band (nominal frequency 2 700-3 000 MHz), C-band (nominal frequency 5 250-5 725 MHz), and X-band (nominal frequency 9 300-9 500 MHz). The exact frequency values of assigned bands are found in accepted standards (IEEE 2002).

The S-band (2 700-3 000 MHz, 10.7 cm nominal wavelength) is the best choice overall in terms of quantitative accuracy and long range performance. This is due to the low values of attenuation for both gaseous absorption and attenuation in precipitation (Fabry, 2015; Doviak, 1993). The longer wavelength also benefits mitigation of range – Doppler ambiguity issues (Doviak, 1978 and 1979). However, cost is a factor in the choice of S-band because the longer wavelength requires larger hardware components and a larger antenna for given requirements for beamwidth and gain.

The C-band (5 250-5 725 MHz, 5.4 cm wavelength) is generally employed in temperate climates, and in countries with reasonably small geographic areas requiring coverage. It can be a relevant compromise between the above-mentioned parameters, allowing rain detection at long ranges (up to 200 km) although its quantification would be in fact limited beyond 100 km and offering the advantage of lower cost resulting from both lower power and smaller antenna size compared to lower-frequency radars having the same spatial resolution.

X-band (9 300-9 500 MHz, 2.5-3.2 cm wavelength) weather radars are more sensitive and can detect smaller particles but, since experiencing higher attenuation, are used for only very short range weather observation (about 50 km). These radars are used for studies on cloud development because they can detect the tiny water particles and are also used to detect light precipitation such as snow. In addition, due to their small size, X-band weather radars are often used as mobile portable units. These radars are also used to detect wind variation in particular for aeronautical purposes (wind shear, vortex, …).

4.2.9.2 Attenuation

Electromagnetic waves are attenuated by water vapour, gaseous absorption, clouds, and precipitation when propagating through the atmosphere (Fabry, 2015). By far the greatest attenuation is caused by precipitation, especially heavy rain. The propagation physics are such that the rate of attenuation (in dB per unit length) at C-band (5.0 cm) is about 6 to 8 times that of S-band (10.0 cm) depending on rain rates (Bean and Dutton, 1966, Burrows and Attwood, 1949). The attenuation problem for X-band is far worse, with attenuation rates of over 100 times those of S-band and over 15 times greater than C-band for rain rates of 6 mm/hr.

The severe impact of attenuation at shorter wavelengths is well documented in the literature. Direct comparisons of performance between 5 and 10 cm radars were done by the National Severe Storms Laboratory

in the 1980's and these tests demonstrated that use of 5 cm wavelengths in heavy rain could seriously impact severe storm forecasting and warning operations (Allen, 1981).

Attenuation correction becomes problematic for shorter wavelengths because very precise power measurement accuracy is required (Hitschfeld, 1954). The reflectivity calibration accuracy requirements necessary for C and X-band to support attenuation correction algorithms exceed current requirements for the United States' Next Generation Radar (NEXRAD) program and are difficult to achieve in practice. The introduction of polarimetry to weather radars has changed the situation consideably because the differential phase provides estimates of the attenuation which do not depend on the reflectivity calibration accuracy.

A somewhat related issue with attenuation drives the need for meteorological radars to employ linear polarization. At the start of the U.S. NEXRAD Weather Surveillance Radar – 1988 Doppler (WSR-88D) S-band radar deployment, the system featured elliptical polarization. This was done in order for efficient and cost effective hardware design for the transmission and reception of the RF signal. However, system managers quickly discovered that depolarization in heavy rain severely impacted operations and the radar was modified to employ linear horizontal polarization (Sirmans, 1993). Because polarization is a factor in considering susceptibility to interference, the current ability to use linear polarization (horizontal and/or vertical), should be preserved.

4.2.9.3 Maximum unambiguous range and velocity estimates

The choice for frequency of meteorological radar also defines the performance characteristics of maximum measurable wind speed and maximum range. In pulsed radar, the time between pulses determines the maximum unambiguous range[5] of the radar. The reflection from a pulse must return to the receiver before the next pulse is transmitted, or the received pulse becomes ambiguous. In Doppler radar systems, the pulse repetition frequency (PRF) determines the maximum unambiguous range and velocity that the radar can measure (Doviak, 1979). In the design of the radar, the designer is limited by the unambiguous range-velocity product, a constant given by:

$$R_m \cdot V_m = c\frac{\lambda}{8} \tag{4-11}$$

where:

R_m: radar unambiguous range (maximum range the radar can make a measurement)

V_m: radar unambiguous velocity (maximum velocity the radar can measure)

c: speed of light (3×10^8 m/s)

λ: radar signal wavelength.

The wavelength of the signal, set by the radar frequency, is the only parameter at the discretion of the radar designer in order to maximize the maximum range and maximum velocity measurement of the radar. A reduction in wavelength requires a reduction in the effective range, effective velocity measurement capability, or a combination of both by the same magnitude as the increase in frequency. In order to limit ambiguity effect and improve the range-velocity product, modern weather radars, in particular in C-band, often make use of different emission schemes combining different PRFs (see § 4.2.4).

Values are given for different technologies: magnetrons, klystrons, and TWTs, the latter having the capability to deliver short emitted pulses characterized by wider emission spectra. Some magnetrons show a frequency shift of less than 1 MHz over a wide range of ambient temperatures. Fast scanning radars require a large amount of spectrum, 10 MHz for example, due to the use of pulse compression.

Even at the longer wavelengths of S-band, it can be difficult to achieve acceptable radar performance over long ranges and large velocity spans. For example, the U.S. NEXRAD program employs numerous mitigation

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[5] The maximum unambiguous range is the longest range to which a transmitted pulse can travel and return to the radar before the next pulse is transmitted. In other words, the maximum unambiguous range is the maximum distance that radar energy can travel round trip between pulses and still produce reliable information.

methods such as multiple scans at the same elevation using different PRFs and systematic phase coding. These issues become much more challenging at shorter wavelengths.

4.2.9.4 Echo coherency

The limit on unambiguous velocity (Nyquist Frequency) is determined by the relationship between PRF and wavelength. The Nyquist co-interval (range of unambiguous velocities) is directly proportional to wavelength. The relevant equation is given by:

$$V_a = \frac{\lambda \cdot PRF}{4}$$

Thus, for a given PRF, the wavelength establishes the Nyquist co-interval, which in turn limits the accuracy of Doppler estimates in terms of the width of the spectrum. When the spectrum width becomes large relative to the Nyquist co-interval, the radar samples become incoherent between pulses and estimate accuracy decreases. Spectrum width can increase (spectral broadening) and become a large portion of the spectrum due to several factors including turbulence, shear, and fall speeds (Fabry, 2015, Section 5.2). If the spectrum width exceeds more than about $(2\pi)^{-1}$ of the Nyquist co-interval, Doppler velocity estimate variance increases at an exponential rate (Doviak, 1978).

Because the effects of turbulence and shear increase as the radar sample volume increases, spectrum width is a function of radar effective beamwidth and range. The "coherency range" can be defined as the maximum range over which acceptable quality Doppler estimates can be obtained. For a given beamwidth, the longer wavelengths (such as 10 cm, S-band) are preferred.

4.2.9.5 Resonance effects – quantitative intensity measurements

The effective backscatter cross section of spherical particles depends highly on the incident signal wavelength as well as the diameter of the sphere (Rheinstein, 1968). For accurate reflectivity estimates, which are a measure of the backscatter cross sections, the power returned must be a linear function of drop size. This dictates that the radar backscatter occurs in the Rayleigh region and the Mie region, which is very non-linear, should be avoided for normally expected rain drop diameters (Fabry, 2015). Resonance effects, in addition to attenuation, can have negative effects on polarimetric variable estimates (Zrnic, 2000). As Zrnic describes, at 5 cm wavelength, resonance occurs for drop sizes larger than about 5 mm and the polarimetric variable exhibit non-linear (non-monotonic) behaviour making accurate quantitative estimates impossible. Effects on correlation coefficient are quite obvious for C-band in particular for reflectivity values greater than 30 dBz (Ryzhkov, 2005).

The uncertainty in the relationship between drop diameter and backscatter cross section in the Mie region can preclude acceptable reflectivity estimates for shorter wavelengths. At attenuating wavelengths, small errors in radar calibration constants cause large errors in the estimated rain rates (Hitschfeld, 1954).

4.2.9.6 Conclusions

The choice of the frequency range for meteorological radars is linked with the coverage range required. If long coverage range is required or in geographical areas where heavy rains are typical, S-band permits higher quality estimates for intensity based parameters and for Doppler estimates. In other geographical areas or at shorter ranges, C- and X-band radars are more adequate, respectively. Other major considerations are the inability to sufficiently mitigate range and velocity ambiguities due to the shorter first trip ranges necessitated by PRFs that are high enough to permit processing of accurate Doppler estimates. Other data accuracy impacts are due to resonance effects (Mie versus Rayleigh scattering) resulting in non-linear relations between the return power (backscattered signal) and the drop size distributions of precipitation. This precludes accurate rain rate estimation and seriously degrades particle identification algorithms.

4.2.10 Vulnerabilities of weather radars

A weather radar determines range to targets (weather) by measuring the time required for an emitted signal to travel from its transmitter to the target and return to the radar site. The travel time is a function of path length, and the accuracy with which it can be measured is critically dependent on the pulse rise- and fall-times. The

leading or trailing edge of a pulse is the marker by which arrival time of a returned pulse is measured, and the shorter it is, the greater the possible precision of the measurement.

The preservation of short pulse transition times requires phase linearity in the transmitter and receiver hardware over a relatively broad band. Required bandwidth is roughly proportional to the shorter of the two pulse transition times, and attempts to reduce the bandwidth of the emitted signal (by additional filtering, etc.) below the necessary value degrade system accuracy. The necessary bandwidth often surprises those not familiar with radar systems. Received interference within the radar's necessary bandwidth also degrades performance.

It must also be reiterated that while most radiocommunication transmissions involve a single traversal of a path between antennas having known characteristics, a radar signal must cover the path twice with an intervening reflection from objects (raindrops, hailstones, wind-borne debris) not designed for that purpose. The resulting received signals are extremely weak.

Despite frequently using large transmitter powers and highly sensitive receivers, radars are extremely vulnerable to noise and interference.

4.2.10.1 Types of possible interference

A weather radars ability to accurately depict the current status of atmospheric conditions can be degraded by various forms of interference which can limit, or in the worst case nullify, the radars ability to detect the speed and direction of the wind at various altitudes, provide relevant quantification of rain rates and accumulation, locate and track hurricanes, typhoons, tornadoes, gales, and other storm-related phenomena. Due to the sensitivity of the radars, interfering signals have the potential to significantly reduce the weather radar performance. As such, it is important to identify the types of interference that can degrade the radars operational capabilities.

Constant, time varying and pulse like intrusive signals are the primary types of interference that can be experienced by weather radars. Once these forms of interference have been identified, one can then establish the maximum interference level that meteorological radar systems can withstand before their forecasting capability is compromised.

Protection criteria levels for meteorological radars can be found in ITU-R Recommendations M.1849-1 as a maximum $I/N = -10$ dB for constant interference.

4.2.10.2 Impact of constant interference

4.2.10.2.1   Geographical coverage

Constant interference can decrease the operational range of the radar resulting in limiting the geographical area of coverage due to the corresponding noise increase.

A protection criteria of $I/N = -10$ dB corresponds to a noise or energy increase of 0.5 dB.

On the principle that radars are calibrated in order to coincide with the level of receiver noise (i.e. about -113 dBm) with the 0 dBz reflectivity level at 100 km, a noise increase changes the nominal conditions of the radar, decreasing its operational range.

Current coverage of typical C-Band meteorological radars roughly extends up to 200 km. Table 4-3 summarizes the losses in range and coverage versus interference and noise increases.

TABLE 4-3

Loss in range and coverage

Noise increase (dB)	Corresponding *I*/*N* (dB)	Loss in coverage (km)	Loss in coverage (% relative to surface)
0.5	−10	11	11%
1	−6	22	21%
2	−2.3	42	38%
3	0	59	50%
4	1.8	75	61%
5	3.3	88	69%
6	4.7	100	75%
7	6	111	80%
8	7.3	121	84%
9	8.4	130	88%
10	9.5	137	90%

4.2.10.2.2 Rain rate

Constant interference also creates an increase of the energy received by the radar that can impact the reflectivity measurement that is associated with various types of precipitation (e.g. rain, snow and hail). Table 4-4 summarizes the percentage increase for several precipitation events as interference (noise) increases.

Following the description in § 4.1.2, the precipitation rate corresponding to a certain reflectivity level (dB) is given by:

$$z = AR^B$$

where:

> z: reflectivity
>
> A: scattering constant
>
> B: rate multiplier

and

> z $= 10 \log z$ (dBz)

where:

> dBz: reflectivity (dB).

Rearranging terms and solving for R yields the following equation:

$$R_{(mm/h)} = \left(\frac{10^{\left(\frac{dBz}{10} \right)}}{200} \right)^{\left(\frac{1}{1.6} \right)}$$

Assuming a constant energy increase, C, the resulting rain rate is:

$$R_{(mm/h)} = \left(\frac{10^{\left(\frac{dBz + C}{10}\right)}}{200} \right)^{\left(\frac{1}{1.6}\right)}$$

The rain rate increase in percentage is then a constant that is given by:

$$p(R_{(mm/h)}) = 100 \times \left(10^{\left(\frac{C}{16}\right)} - 1 \right)$$

Table 4-4 lists typical scattering constants and rate multipliers for several types of precipitation[6].

TABLE 4-4

Scattering constants and rate multipliers for various precipitation events

Variables	Stratoform rain	Convection rain	Snow	Hail
Scattering constant (A)	200	500	2 000	2 000
Rate multiplier (B)	1.6	1.5	2	1.29

Table 4-5 summarizes the percentage rain increase for several precipitation events.

TABLE 4-5

Precipitation rate increase

Noise increase (dB)	Corresponding *I/N* (dB)	Stratoform rain rate increase (%)	Convection rain rate increase (%)	Snow rate increase (%)	Hail rate increase (%)
0.5	−10	7.5	8.0	5.9	9.3
1	−6	15.5	16.6	12.2	19.5
2	−2.3	33.4	35.9	25.9	42.9
3	0	54.0	58.5	41.3	70.8
4	1.8	77.8	84.8	58.5	104.2
5	3.3	105.4	115.4	77.8	144.1
6	4.7	137.1	151.2	99.5	191.8
7	6	173.8	192.9	123.9	248.8
8	7.3	216.2	241.5	151.2	317
9	8.4	265.2	298.1	181.8	398.5
10	9.5	321.7	364.2	216.2	495.9

---

6   Stratoform rain, convection rain, snow and hail scattering constants and rate multipliers are derived from measurements.

These calculations show that, irrespective of the rain value and precipitation type, the percentage of overestimation corresponding to a given constant energy increase is also constant, and hence cannot be neglected.

Also, considering the reflectivity calculation for a given pixel that are based on the average (dBz), over all estimates, and the related standard deviation, it is worth noting that an increase in interference would not modify the radars ability to detect rain cells (i.e. a measurement not considered as a rain cell will still not be considered as such) but would only have an impact on the rain rate.

It is also interesting to note that either for the loss in coverage or the rain rate overestimation, the current agreed protection criteria of -10 dB I/N represents radar performance degradation in the range of 7 to 11%, comparable to performance degradation percentages generally agreed upon for all radiocommunication services.

An example of impact of a constant interference on a radar precipitation mode can be seen in Fig. 4-12. It is important to highlight that, although being a constant interference, the variation in impact is due to the rotation of the antenna, the maximum interference (in green on this picture) being produced in the azimuth of the interfering source.

FIGURE 4-12

Example of interference to precipitation mode of a weather radar

Meteo-0 4-12
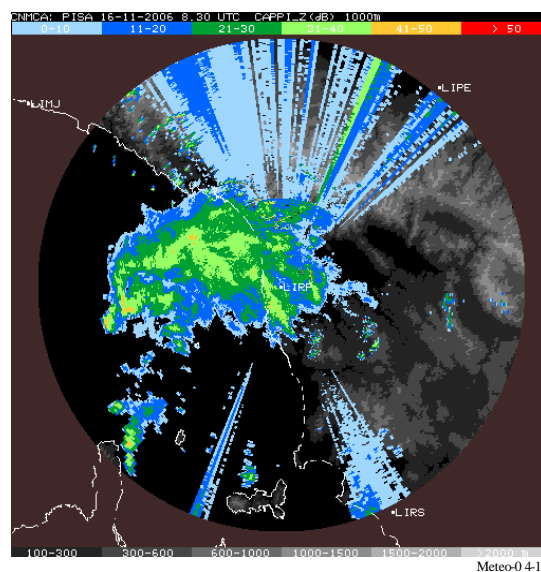
4.2.10.2.3 Wind measurement

In the case of Doppler measurements, the assessment of the impact of a given constant interference is somehow different and would in particular depend on how the phase of the interfering signal could modify the phase of the wanted signal impacting the derived wind measurement.

This latter assumption is certainly not trivial to determine and will be signal and/or environmentally dependent. However, it is proposed to consider the different situations on a theoretical basis:

−   *Case 1* − If the phase of the interfering signal detected by the radar is random, it means that the resulting vector would be statistically null; whatever would be its level. Hence, it would theoretically not have any impact on the wind measurements.

−   *Case 2* − On the contrary, if the detected phase is not random and almost constant, it would result in a constant vector with a certain module and the impact on the wind measurement will depend on both

the phase and module of such vector. However, the determination of such impact, even for a constant interference level is likely not to be easy and is hence not made at this point.

In addition, one can also assume that when the level of interference is much lower than the wanted signal, the phase of this latter is not modified whereas, on the contrary, if the interfering signal is much higher, then the phase detected by the radar will be the phase of the interfering signal. In this latter situation, the discussion on Cases 1 and 2 above will remain. In between these two situations, i.e. when the levels of both the interfering and wanted signals are consistent, it seems quite difficult to assess which of the signal will control the phase detection.

4.2.10.3 Impact of pulsed interference

Pulsed interference can have a significant impact on the reflectivity data and could result in a returned data that cannot reliably produce an image of targets in the atmosphere. An example of this can be seen in Fig. 4-13.

FIGURE 4-13

Comparison of interference free versus interference corrupted on precipitation mode of a weather radar

Interference free   *Interference corrupted*   Meteo-0 4-13
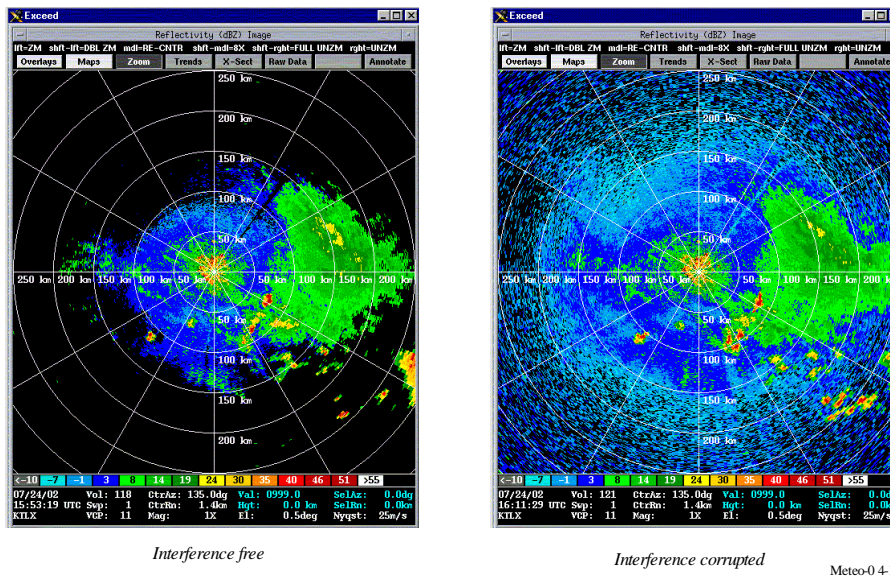
An additional example of interference to meteorological radar from a single indoor low power transmitter can be seen in Fig. 4-14.

FIGURE 4-14

Interference to meteorological radar (precipitation mode)

Meteo-04 -14

4.2.10.4 Interference from wind farms

In recent years, increasingly larger wind turbines are being constructed and the number of typical generation facilities (or wind farm, including many wind turbines) is dramatically increasing. Wind turbines and farms, even at quite large distances present a high potential to degrade meteorological data over very large areas and do have a non-negligible impact on weather nowcasting and forecasts.

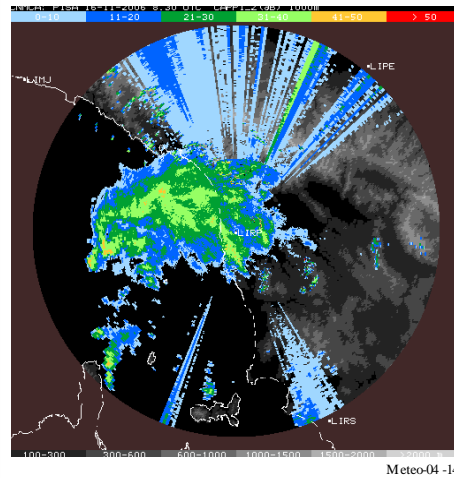For accurate weather forecasting, weather radars are designed to look at a relatively narrow altitude band. Due to the sensitivity of the radars, wind turbines, if deployed with line of site of a weather radar facility, can block the onward propagation of the radar signals, cause reflectivity clutter returns, and produce wake-turbulence-induced radar echoes. These interference mechanisms can result in false radar estimates of precipitation accumulation, false tornadic and mesocycle signatures, misidentification of thunderstorm features and incorrect storm cell identification. In addition, the interference mechanisms can result in degraded radar performance and negatively impact forecast and warning operations. There are three mechanisms through which the performance can be degraded; masking, clutter and backscatter.

4.2.10.4.1 Masking

Any geographical feature or structure which lies between the radar and the target will cause a shadowing or masking effect. It is possible that, depending on their size, wind turbines may cause shadowing effects. Such effects may be expected to vary, depending upon the turbine dimensions, the type of transmitting radar and the aspect of the turbine relative to it (height, blade angle, rotation rate, and position relative to the radar of the turbine).

4.2.10.4.2 Clutter

Radar returns may be received from any radar-reflective surface. In certain geographical areas, or under particular meteorological conditions, radar performance may be adversely affected by unwanted returns, which may mask those of interest. Such unwanted returns are known as radar clutter. For a weather forecaster, a wind turbine or turbines in the vicinity of weather radar can present operational problems.

Ground clutter signals exhibit large reflectivity, near-zero Doppler shift, small spectrum width, and are consistently localized. Compared to commonly occurring ground clutter (GC), interference caused by wind turbines is a much more difficult challenge. Direct reflections will be received from both the tower (stationary) and the blades (non-stationary). Like GC, the wind turbine clutter (WTC) signal should still have a significantly large reflectivity, with a possible modulation due to blade rotation causing a systematic variation in radar cross-section.

The Doppler shift will be affected by several factors, including the blade rotation speed and rotor orientation with respect to the radar beam. Doppler velocities should be maximum when the rotor is oriented 90 degrees from the radar line-of-sight and near zero when the rotor is facing either away or toward the radar. Since the resolution volume of the radar will likely encompass the entire wind turbine structure, it is expected that the spectrum width will be significantly enlarged. This is due to the blade rotation away and toward the radar. Multiple turbines within one resolution volume would only exacerbate this effect.

4.2.10.4.3   Backscattered energy from turbulent eddies

In addition to WTC signals caused by reflections from the actual wind turbines, backscattered energy from turbulent eddies in the wake of the wind farm may be observed. It is expected that these echoes would exhibit characteristics similar to clear-air backscatter from discontinuities in the refractive index at the Bragg scale of the radar. These wake echoes would drift with the wind field and would likely have much lower reflectivity compared to the direct reflections from the turbines. Nevertheless, they could significantly enlarge the radar coverage area affected by WTC and thus exacerbate the problem.

4.2.10.4.4   Examples of wind turbine clutter

Two distinct examples of interference from Wind Farms[7] are provided in Fig. 4-15 [Palmer and Isom, 2006]. As expected, the reflectivity shows large values near 45 dB$_Z$ with sporadically large spectrum widths of over 10 m/s. The relatively small region of high reflectivity to the south-west of the radar is clearly visible and matches the location of a wind farm that is approximately 45 km from the weather radars location.

FIGURE 4-15

Examples of wind farm interference to weather radar under clear-sky conditions
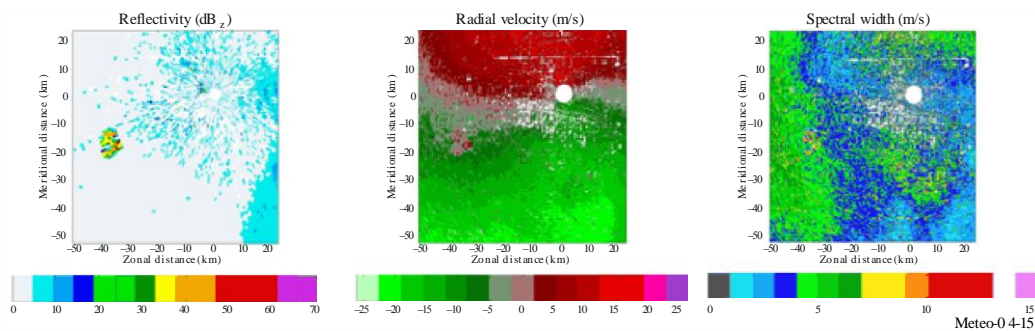
Figure 4-16 shows the same wind farm during a thunderstorm event.

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7   Wind Farms are clusters of wind turbines that are used to generate power.

FIGURE 4-16

**Example of interference from a wind farm and its impact upon reflectivity during
an isolated thunderstorm incident**
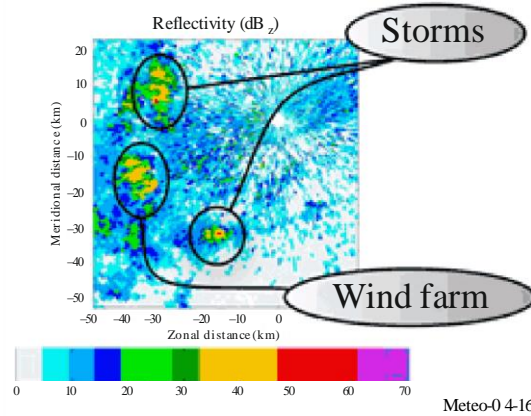
Without prior knowledge, it would be extremely difficult to distinguish between the WTC and the thunderstorms. Since the blades rotate toward and away from the radar, one would expect a near-zero mean Doppler velocity. Of course, the large spectrum widths will reduce the accuracy of the Doppler velocity estimates as illustrated in Fig. 4-17 by small deviations from zero.

FIGURE 4-17

Examples of Doppler velocity data estimates during a thunderstorm event
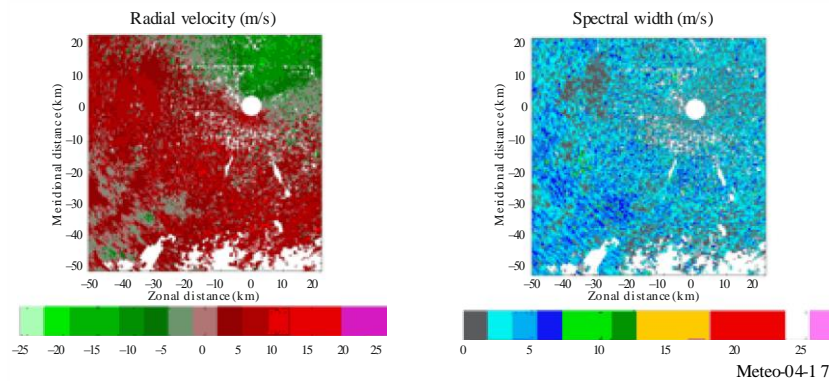
4.2.10.4.5 Impact of WTC on meteorological radar operations and forecasting accuracy

Field studies have been recently conducted that illustrate the impact of WTC upon weather radars. These studies have shown that wind turbine farms can have a significant effect upon meteorological radars and as such can degrade the accuracy of detecting severe weather events.

These analyses have clearly shown that the clutter produced by a wind turbine will be present over a large sector (several tens of degrees) compared to the direction of the wind turbine, even at quite large distances. Thus the impact of the wind turbines on reflectivity operation of weather radars cannot be neglected.

In particular, the analysis have shown that the impact of one single wind turbine on weather Radars Doppler mode is highly significant even at distances of several tens of kilometres. One can also stress that at distances lower than 10 km, all radar data will be erroneous at every azimuths, even at 180° from the sector in which the wind farm resides.

Some form of WTC mitigation will be required in order to protect meteorological radars from harmful interference from wind turbine farms. Before any final conclusions can be made regarding processing methods to mitigate WTC, additional studies of WTC should be conducted in order to understand the full extent and the impact of WTC on the meteorological radars. Once this has been defined, methods to mitigate WTC may need to be developed given the expected growth of wind-power based generation systems.

Pending the result of ongoing studies on mitigating WTC interference to meteorological radars, the current solution to avoid or limit impact of wind farms is to ensure separation distances between the two systems. For example, some European countries are currently considering the following recommendations:

1   that no wind turbine should be deployed at a range from radar antenna lower than:

–   5 km for C-band radars

–   10 km for S-band radars

2   that projects of wind parks should be submitted to an impact study when they concern ranges lower than:

–   20 km for C-band radars

–   30 km for S-band radars.

4.2.11   Vulnerabilities of systems sharing spectrum with weather radars

As noted above, the transmitter power and antenna gain of weather radars are typically quite high to compensate for extended path lengths (typically around 100 dBW peak e.i.r.p.). These characteristics tend to extend the range over which a radar can interfere systems on the same frequency (with due recognition given to the width of a radar channel). There have also been cases in which radar and fixed microwave links, which have co-existed for some time, become incompatible when the microwave system is upgraded from analogue to digital equipment with a greater vulnerability to pulsed interference.

4.2.12   Future trends

Major hardware upgrades to various administrations' meteorological radar systems are in progress. Ongoing generation of upgrades includes implementation of polarimetric radar, which adds vertical polarization to the currently used horizontal radar waves. As of 2016, all NEXRAD radars in USA and roughly half of OPERA radars in Europe have been upgraded to dual polarisation.

Additional techniques to further improve the performance of meteorological radars are also under way. Foremost among these are various algorithms for resolving range/velocity ambiguities, increasing data acquisition speed, reducing the effects of artefacts, decreasing clutter and efficient processing of signals to provide meteorological estimates that are as accurate as possible. Other endeavours include combined use of weather and profiling radars. A modest effort is devoted to studies of lightning and its hazards, to determine whether its onset and termination might be predictable.

Researchers have adapted phased array radar technology for use in weather surveillance applications. The phased array will replace mechanically steered parabolic dish antennas with an electronically steered array antenna. This change will enable more flexible scanning strategies and more rapid updates of changing weather conditions. Early tests of the phased array radar system have proved promising. Phased array technology will increase fundamental understanding of storm evolution, in turn leading to improved computer models, more accurate forecasts and earlier warnings. In addition, this technology has the potential to increase the average lead-time for tornado warnings well beyond the current average of 13 min. System enhancements are more economically implemented via improvements to the receiver and signal processing subsystems. There is a possibility that the phased array upgrade (if implemented) will not reuse the existing transmitter, which will be replaced by distributed transmit/receive modules in the phased array. Possible implementation of phased array meteorological radar has been discussed in some regions.

A potential does exist for the deployment of CASA (Centre for collaborative adaptive sensing of the atmosphere) based X-band weather radar systems within the 8 000 MHz to 12 000 MHz portion of the frequency spectrum. The National Science Foundation established a new engineering research centre for collaborative adaptive sensing of the atmosphere (CASA) in September 2003 to develop small, low-cost radars

for high-resolution sensing of the lower atmosphere. Meteorological conditions in the lower troposphere are grossly under-sampled, inhibiting forecasts and model initialization in the region where storms develop. The high spatial-density CASA radars will have the potential of detecting evolving weather patterns in the region of the lower atmosphere that often lies below existing operational Doppler radar coverage (i.e. the lowest three kilometres). CASA radars will be placed on cell phone towers or other existing infrastructure with large data transmission capabilities. Unlike the existing pre-programmed radar network, the collaborative CASA radars will communicate with one another, and adapt their sensing strategies in direct response to the evolving weather and changing end-user needs. These radar data can be incorporated into numerical weather prediction models for more complete data initialization.

One should also finally note the SENSR project in the US for which weather and ATC radars (primary and secondary) shall be combined in one radar hardware (a one-fits-it-all approach).

These future trends will need to be tracked and, as technologies evolve, will have an impact on any future interference mitigation strategies and protection criteria definitions.

4.3   Wind profiler radars (WPRs)

Wind Profiler Radars are used to obtain the vertical profiles of the wind over an unattended and sometimes remote area by detecting the tiny fraction of emitted power backscattered from turbulence in the clear atmosphere. Figure 4-18 is a photograph of a typical wind profiler radar installation.

FIGURE 4-18

Photo of wind profiler installation

Meteo-04-14
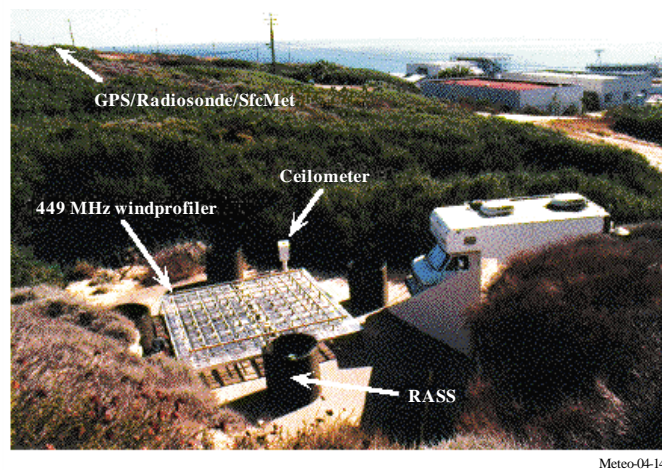
One of the major advantages of wind profilers to other wind measurement systems is their ability to continuously monitor the wind field. In addition, they can also be used to detect precipitation, measure major features in the vertical velocity field (gravity waves and convective updrafts), estimate the intensity turbulence and measure atmospheric stability. They can also provide detailed information on the vertical profile of the atmospheric virtual temperature through the addition of a Radio Acoustic Sounding System (RASS)[8].

_____

[8] RASS utilizes an acoustic source that is matched in frequency so that the wavelength of the acoustic wave is matched to half the wavelength of the radar transmitted electromagnetic wave (Bragg condition). RASS measures the speed of the acoustic wave which is dependent upon temperature. In this way RASS provides a remote measurement of the atmospheric virtual temperature.

4.3.1   User requirements

A good way to examine the impact of user requirements upon wind profiler operating parameters and design is to consider the following simplified equation based on [Gossard and Strauch, 1983]:

$$SNR = \text{const } \frac{\overline{P}_t \, A_e \, \Delta_z \, \lambda^{1/6} \, t_{obs}^{1/2}}{T_{sys}} \; \frac{C_n^2}{z^2} \qquad (4\text{-}12)$$

where:

$\overline{P}_t$:   average transmitted power (W)

A_e: effective aperture (degrees)

Δ_z: height resolution (m)

z: height (m)

λ: wavelength (m)

t_{obs}:   observation (averaging) time (s)

T_{sys}:   system noise temperature (K)

C_n^2 :   structure parameter (dimensionless).

This equation is only valid in the inertial sub-range of atmospheric turbulence. Indeed, the structure of atmospheric turbulence is physically limiting the usable wind profiler radar wavelength range to about 10-0.2 m (30 to 1 500 MHz). Below the lower limit of this inertial sub-range, turbulence is rapidly dissipated by viscosity to heat. For this reason shorter wavelengths cannot be used for wind profiling due to the lack of measureable refractive index fluctuations at the very small scale.

The structure parameter of the refractive index is independent of frequency inside the relevant Bragg wavelength range bounded by the limits of the inertial subrange, but has a strong dependence on height. The remaining frequency dependence is mainly contained in the wavelength factor, with the system noise temperature including a significant contribution from cosmic noise for wavelengths greater than about 1 m.

A user requirement for high temporal resolution diminishes signal-to-noise ratio by reducing the averaging time. The requirement may be satisfied by selecting some combination of:

–   large aperture;

–   high peak power and high pulse repetition frequency (PRF) to increase average power;

–   long wavelength; and

–   operation over a range of heights close to the radar where high PRF does not cause range ambiguity problems and where atmospheric backscattering and inverse-height-squared are relatively large.

A user requirement for high vertical resolution diminishes signal-to-noise ratio by requiring short pulses and so reducing mean power. High vertical resolution requires large bandwidth. This requirement may be satisfied by selecting some combination of:

–   large aperture;

–   high peak power, high PRF, and pulse compression to increase the average power;

–   long wavelength; and

–   operation over a range of heights close to the radar where high PRF does not cause range ambiguity problems and where atmospheric backscattering and inverse-height-squared are relatively large.

Note that using pulse compression (to increase pulse length) means that the lowest range gate must be increased in height.

A user requirement for obtaining wind data at high altitudes diminishes signal-to-noise ratio by decreasing the inverse-squared-height and, while not obvious in the equation, by the decrease with height of the structure

parameter and the compression of the inertial sub-range from the short wavelength (high frequency) end with increasing height. This requirement may be satisfied by selecting some combination of:

– large aperture;

– high peak power and pulse compression to increase the average power;

– long wavelength; and

– long averaging times.

The user requirement for reliable all-weather operation requires an adequate signal-to-noise ratio also when low scattering conditions exist in the atmosphere. Typical situations are wintertime low humidity periods and cases of low turbulence, i.e. in the core of jet streams in the 10-15 km altitudes. The requirement can be satisfied by suitable selection of:

– frequency band;

– high average power and antenna aperture;

– higher receiver sensitivity; and

– low level of interference and system noise.

4.3.2 Operational and frequency aspects

Large antenna aperture and high average emitted power are expensive. The cost of the antenna and power amplifier of a wind profiler radar often constitutes more than half the total cost of an installed system. Hence, technology developments in these areas are rather expensive options for improving performance.

In the case of antenna aperture, however, there is another factor to consider which establishes a minimum size. WPR operate by successively swinging the main beam to at least three independent directions. Current systems typically use two or four orthogonal azimuths at elevation angles of about 75° and often to the vertical to acquire data. More recent antenna designs allow for much enhanced flexibility in beam steering. The antenna beamwidth must be narrow enough to delineate the multiple beam positions. 3 dB full-width beamwidths of 5° to 10° are usable and correspond to antenna gains of 33 dBi to 27 dBi, respectively. Gain determines the effective aperture through the equation (4-13):

$$A_e = 10^{G/10} \, \lambda^2/4\pi \qquad\qquad (4\text{-}13)$$

Because of interference and congestion in the radio-frequency spectrum and its consequent regulation, wind profiler radar frequencies cannot be freely chosen. Some demanding applications, such as the MU radar in Japan and those at the Eastern and Western Launch Ranges in the United States of America, have resulted in the use of very large (about 10 000 m^2), powerful (250 kW or more peak, 12.5 kW or more average), short pulse (1 µs) radars operating near 50 MHz. Researchers have also operated other profilers on a non-interference basis at frequencies between 40 and 70 MHz.

Profilers operating in the range of 400-500 MHz have been designed to:

– measure wind profiles from about 0.5-16 km above the radar with vertical resolutions of 150-250 m at low altitudes and 300-1 000 m at high altitudes using antennas with typically 32-34 dBi gain;

– mean powers of about 500 W and 2 000 W when probing low and high altitudes, respectively;

– while operating with necessary bandwidths of less than 2 MHz.

Increasing the operational frequency of a wind profile radar provides a higher degree of measurement resolution at the cost of lowering the overall height measurements. As such, profilers operating at 915 MHz and 1 270-1 375 MHz are typically regarded as boundary layer profilers, capable of measuring the wind profile in only the lowest few kilometres of the atmosphere. These perform with vertical resolution of about 100 m using antennas with gains below 30 dBi and mean powers of about 50 W while operating with necessary bandwidths of approx. 2.5 MHz.

As an example mobile profiling system operating at 924 MHz produced the plot of wind velocity vs. altitude (see Fig. 4-19). The orientation of each barb represents wind direction as a function of altitude (vertical axis) and time (horizontal axis), while its colour represents wind speed.

FIGURE 4-19

Wind velocity vs. altitude

Meteo-04-19
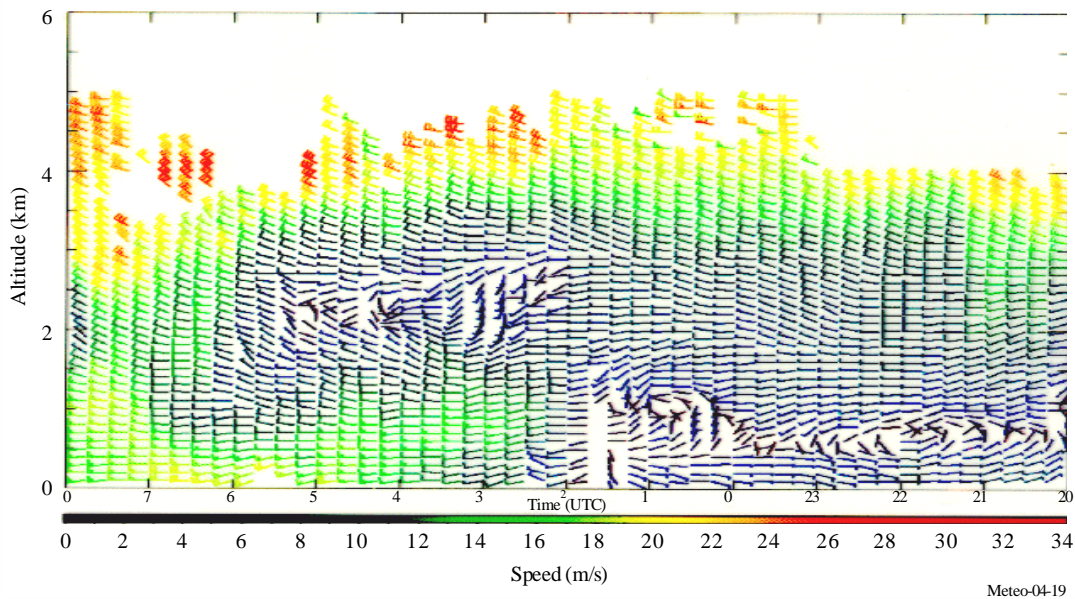
4.3.3   Present and future spectrum requirements

Wind profilers radars are ground-based systems with antenna heights of one or two meters and vertically directed beams. Geographical separation and terrain shielding are effective protection against interference to and from other profilers. Hence, an affordable network of wind profilers, say separated by at least 50 km over level terrain – less over more rugged or treed terrain – could operate on the same frequency. Under these rationales, profilers tend to be compatible with most ground-based services.

It is generally agreed that 2 to 3 MHz of bandwidth are required near 400 MHz and 2.5 MHz near 1 000 MHz or 1 300 MHz and it can be assumed that provisions of Resolution **217 (WRC-97)**, as below, are sufficient to fulfil these requirements:

> "... to urge administrations to implement wind profiler radars as radiolocation service systems in the following bands, having due regard to the potential for incompatibility with other services and assignments to stations in these services, thereby taking due account of the principle of geographical separation, in particular with regard to neighbouring countries, and keeping in mind the category of service of each of these services:

> –   46-68 MHz in accordance with No. **5.162A**

> –   440-450 MHz

> –   470-494 MHz in accordance with No**. 5.291A**

> –   904-928 MHz in Region 2 only

> –   1 270-1 295 MHz

> –   1 300-1 375 MHz;"

> "... that, in case compatibility between wind profiler radars and other radio applications operating in the band 440-450 MHz or 470-494 MHz cannot be achieved, the bands 420-435 MHz or 438-440 MHz could be considered for use;"

4.3.4   Sharing aspects of wind profilers

The bands for profiler use allocated by WRC-97 were carefully selected to minimize the likelihood of interference to and from other users of these bands. Before the identification of bands for wind profiler radars

an experimental network was developed in the band 400.15-406 MHz. Operational experience showed operation of wind profiler radars in 400.15-406 MHz caused interference to COSPAS-SARSAT.

As a result, Resolution **217 (WRC-97)** identifies spectrum to be used for WPRs and specifically states that wind profiler radars should not be operated in 400.15-406 MHz. The existence of this experimental network did provide considerable information on wind profiler radar compatibility with other services. The e.i.r.p. spectral density of these WPRs in the horizontal direction is about:

–   −18 dB(W/kHz) at the centre frequency (449 MHz)

–   −36 dB(W/kHz) 0.5 MHz away

–   −55 dB(W/kHz) 1 MHz away

–   −70 dB(W/kHz) 2 MHz away

–   −79 dB(W/kHz) 4 MHz away.

These low values, when combined with low antenna heights and path losses proportional to $1/r^4$ for propagation over the surface of the Earth, result in making geographical separation a very effective sharing tool.

However, in the main beam, the e.i.r.p. spectral density is 57 dB greater and, as a consequence, airborne and satellite-based receivers are subjected to a much higher level of interference. Path losses proportional to $1/r^2$ compound the problem. Subsequent efforts to alleviate the problem with WPR in the band 400.15-406 MHz showed that the modulation used by 404 MHz WPRs has a significant impact upon their sharing characteristics. Currently, the pulses are phase-coded to distinguish the two or three "chips" within each pulse so as to achieve pulse compression. Were no further coding done, the emitted spectrum would consist of lines separated by the PRF. However, one member of a 64-long pseudo-random phase code sequence was imposed on each pulse in succession so that the spectral lines appear at intervals of PRF/64 with line powers reduced by a factor of 64. In addition, the profiler transmitters were turned off under computer control whenever a COSPAS-SARSAT satellite appeared more than 41 degrees above the profiler's horizon. (There being only a few of these satellites, these results in a negligible loss of profiler data.)

The phase coding applied to 404 MHz profiler emissions must be "undone" in the receiver. As a result, interference from other, non-WPR systems appears incoherent and noise-like to the profiler. Hence, the minimum detectable (profiler) signal is about −170 dBm, while interference is troublesome only at levels of −135 dBm or more.

As another example of sharing with WPR, the band 1 215-1 300 MHz was allocated to the radionavigation satellite service at WRC-2000. Since then, some technical studies were performed to assess compatibility between these RNSS systems and WPR's operating in the 1 270-1 295 MHz band. Result of these studies can be found in ECC Report 90. This report concludes that RNSS systems could, under some conditions, interfere and degrade wind profiler operations, at least for three-beam WPRs. This report however list a number of mitigation techniques (hardware or software) that could help overcoming these difficulties. Some of these techniques include selection of antenna pointing, adding beams or implementing WPR frequencies at 1 274 or 1 294 MHz, at nulls of the RNSS modulations, this latter being likely the more simple ones to apply.

The Japan Meteorological Agency (JMA) is operating a Wind Profiler Network and Data Acquisition System (WINDAS) network for the purpose of monitoring the development of and predicting severe weather events. The network consists of thirty-three 1.3 GHz wind profilers installed across Japan that communicate with a control centre which is located at the JMA headquarters in Tokyo (Fig. 4-20).

FIGURE 4-20

An example of a wind profiler radar network

Meteo-04-20
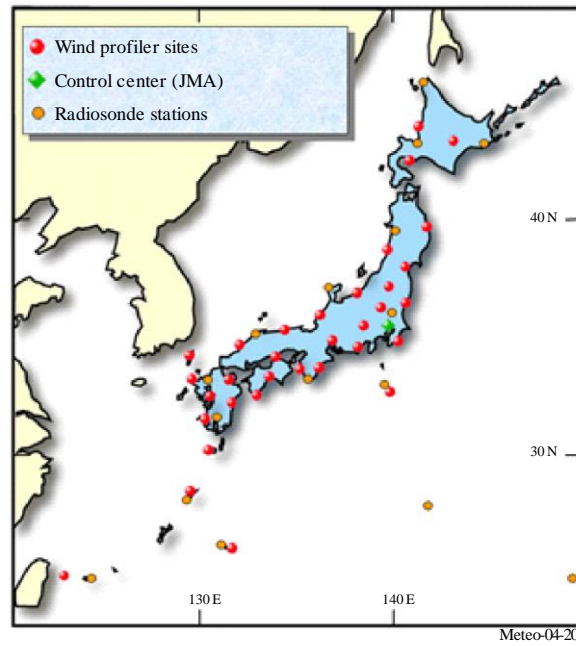
The data is then distributed throughout the world, via the Global Telecommunication System and can also be found on the JMA website (http://www.jma.go.jp/jma/indexe.html). Furthermore the data is combined with data from Doppler radars and commercial aircraft to provide a comprehensive "Upper-air wind analysis".

CHAPTER 5

PASSIVE AND ACTIVE SPACEBORNE REMOTE
SENSING FOR METEOROLOGICAL ACTIVITIES

Page

5.1   Introduction

The existence of meteorological satellites is well known in most of the world and images produced by them are shown regularly on television, in the popular press and on the Internet. The public is nowadays used to seeing colour-augmented, map-registered images showing cloud cover, surface temperatures, snow cover and other weather phenomena, or, less frequent, images showing the distribution of wildfires and the resulting smoke clouds; volcanic ash; and the sea surface temperatures which have received wide public attention because of the *El Niño* phenomenon.

Many of these have in common the fact that they are generated primarily from data recorded using sensors in the visible and infrared regions. However, many of these products and other products are produced using a variety of microwave frequencies either in isolation or in conjunction with measurements at other frequencies.

It is therefore not widely known that spaceborne remote sensing of the Earth's surface and atmosphere, using radio frequencies, from VHF through microwaves and into the upper regions of the spectrum, has an essential and increasing importance in operational and research meteorology, in particular for mitigating the impact of weather and climate-related disasters, and in the scientific understanding, monitoring and prediction of climate change and its impacts.

The impressive progress made in the recent years in weather and climate analysis and forecasts, including warnings for dangerous weather phenomena (heavy rain, storms, cyclones) that affect all populations and economies, is to a great extent attributable to data from spaceborne observations and their assimilation in numerical models.

Recent studies in Europe confirmed that Metop satellites, embarking several different remote sensors (passive and active) makes a major contribution to the performance of Numerical Weather Prediction (NWP), accounting for 25% of the reduction of 24 hours forecast errors due to all observations ingested in real time by models. Because of this high contribution to the reduction of forecast errors, a significant portion of the high socio-economic benefits of weather forecasting – estimated at €61.4 billion per year in the European Union – can be attributed to Metop satellites to the order of €4.9 billion per year.

There are two classes of spaceborne remote sensing widely employed, **passive** and **active**, that operate under the Earth exploration-satellite service (EESS) currently only on non-GSO satellites.

Passive sensing involves the use of pure receivers, with no transmitters involved. The radiation sought by these receivers occurs naturally, usually at very low power levels, which contain essential information on the physical processes under investigation. Of interest are radiation peaks indicating the presence of specific chemicals, or the absence of certain frequencies indicating the absorption of the frequency signals by atmospheric gases. The strength or absence of signals at particular frequencies is used to determine whether specific gases (moisture and pollutants being obvious examples) are present and if so, in what quantity and at what location. A wide variety of environmental information can be sensed through passive sensors operating in frequency bands determined by the fixed physical properties (molecular radiation resonance or absorption) of the substance under examination and whose physical properties cannot be duplicated in other frequency bands. Signal strength at a given frequency may depend on several variables, making use of several frequencies necessary to match the multiple unknowns. The use of multiple frequencies is the primary technique used to measure various characteristics of the atmosphere and surface of the Earth.

Active sensing differs from passive sensing in that it involves both transmitters and receivers onboard a satellite. Normally the signal is transmitted and the reflected signal is received by the same satellite however this not always the case. The uses of active sensing include, but are not limited to, measuring the characteristics of the sea surface such as sea wave height and winds and determining the density of trees in the rain forest.

The issue of compatibility for both classes of remote sensing involves the same problems as those associated with other space services: mutual interference between the satellite receiver and other RF transmitting stations, either on the ground or in space. The resolution of these problems implies well-known techniques, typically related to coordination with other users on the basis of power limitations, antenna characteristics, and time and frequency sharing.

A form of vulnerability peculiar to passive remote sensing satellites, and particularly those having a large area measurement sample, derives from the fact that each measurement can be subjected to accumulated radiation

from a multitude of emitters on the ground, both from in-band emitters and out-of-band emitters. Thus, while a single terrestrial emitter may not radiate enough power to cause errors in passive sensing measurements, a large number of these emitters may be harmful to the measurements being taken through the aggregation of those interfering signals. This aggregation of interference from multiple emitters is the basis for concerns regarding such things as high density fixed service (HDFS) emissions, ultra-wide band (UWB) applications and short-range devices (SRD) or industrial, scientific and medical (ISM) devices. It is the spatial density of such emitters within a measurement area in combination with their individual characteristics which creates a potential problem. The situation tends to be more and more severe with the increased density of such terrestrial active devices and instances of harmful interference have already been reported.

Several geophysical parameters contribute, at varying levels, to the natural emissions of the specific parameter to be observed at a given frequency. Therefore, measurements at several frequencies in the microwave spectrum must be made simultaneously in order to isolate and to retrieve each individual contribution to the overall natural emissions, and to extract the parameters of interest from the given set of measurements. As a consequence, interference that impacts any of a number of "passive" frequency bands could thus have an impact on the overall measurement of a given atmospheric component obtained over a set of prescribed frequencies.

In the case of transmitter-receiver pairs, the nature and characteristics of the signal are known and it is relatively simple to determine whether the signal is being received correctly. The literature is full of useful techniques for dealing with error detection and correction in radiocommunication systems but these techniques are unfortunately of no use when the characteristics of the various received signals are unknown. This is precisely the case with passive remote sensing whose vulnerability to interference is unique because this vulnerability is caused by the non-deterministic nature of the natural signal that the passive sensor is designed to receive and the very low power level of natural radiation measured.

Even very low levels of interference received by a passive sensor may degrade its data and the biggest threat is perhaps that the interference will go undetected, that corrupted data will be mistaken for valid data and that the conclusions derived from the analysis of these corrupted data will be seriously flawed. In most cases, passive sensors are not able to discriminate between natural and man-made radiations and the resulting data errors can be neither detected nor corrected. Therefore, it appears that maintaining data integrity currently depends solely upon the prevention of interference and the use of regulatory limitations on interference and maximum emitter power on a global basis. One can note that a number of provisions in the Radio Regulations use such power limits to active service transmitters for the purpose of protecting passive sensors from in-band or out-of-band interference.

There has been considerable interest in recent years in the use of millimetre-wave cloud radars for research applications. The need for improved understanding of the role of clouds in our climate system has a very high priority in climate change research. Together with recent advancements in millimetre-wave radar technology this research need has been the driving force for development of millimetre-wave cloud profiling radars. Operating mainly near 36 GHz (Ka-band) and near 94 GHz (W-band), these radars now provide the necessary qualitative and quantitative information needed by climate researchers. Their sensitivity to small hydrometeors, high spatial resolution, minimal susceptibility to ground clutter, and their relatively small size makes the millimetre-wave radar an excellent tool for cloud research. They can be operated from fixed ground, mobile ground, airborne, and space-based platforms.

5.2   Passive microwave radiometry sensing

Passive microwave radiometry is a tool of fundamental importance for Earth observation. Under the EESS, passive sensors operate that are designed to receive and measure natural emissions produced by the Earth's surface and its atmosphere. The frequency and the strength of these natural emissions characterize the type and the status of a number of important geophysical atmospheric and surface parameters (land, sea, and ice caps), which describe the status of the Earth/atmosphere/oceans system, and its mechanisms:

–   Earth surface parameters such as soil moisture, sea surface temperature, ocean wind stress, ice extent and age, snow cover, rainfall over land, etc.; and

- three-dimensional atmospheric parameters (low, medium, and upper atmosphere) such as temperature profiles, water vapour content and concentration profiles of radioactively and chemically important trace gases (e.g. ozone, nitrous oxide and chlorine).

Microwave techniques enable observation of the Earth's surface and its atmosphere from Earth orbit even in the presence of clouds, which are largely transparent at frequencies below 100 GHz. This all-weather capability has considerable interest for the Earth observation because more than 60% of the Earth's surface is usually covered with clouds. In addition to this all-weather capability, passive microwave measurements can also be taken at any time of day as they are not reliant on daylight. Passive microwave sensing is an important tool widely used for meteorological, climatological, and environmental monitoring and survey (operational and scientific applications), for which reliable repetitive global coverage is essential.

5.2.1 Spectrum requirements

Several geophysical parameters generally contribute, at varying levels, to natural emissions, which can be observed at a given frequency. Therefore, measurements at several frequencies in the microwave spectrum must be made simultaneously in order to isolate and to retrieve each individual contribution. The absorption characteristics of the atmosphere, as shown on Fig. 5-1, are characterized by absorption peaks due to the molecular resonance of atmospheric gases, and by the water vapour continuum which increases significantly with frequency.

FIGURE 5-1

Zenith opacity of the atmosphere due to water vapour and dry components
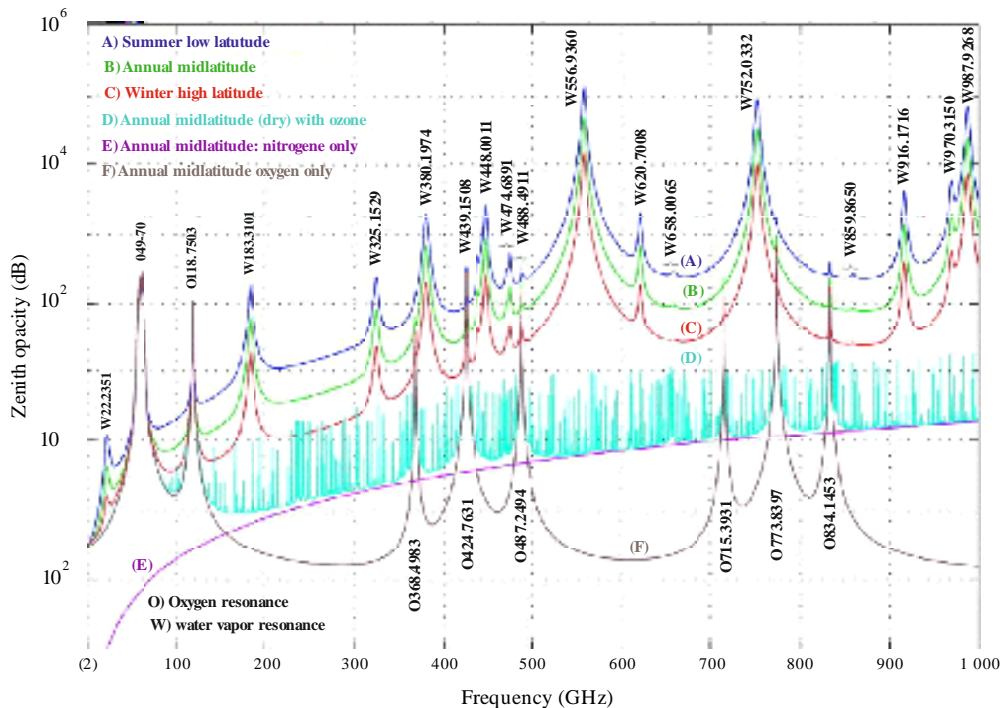
Meteo-05 -01

The selection of the best-suited frequencies for passive microwave sensing depends heavily on the characteristics of the atmosphere:

- frequencies for observation of surface parameters are selected below 100 GHz, where atmospheric absorption is the weakest. One frequency per octave, on average, is necessary; and

- frequencies for observation of atmospheric parameters are very carefully selected mostly above 50 GHz within the absorption peaks of atmospheric gases.

The required frequencies, and bandwidths of interest below 1 000 GHz are listed in Table 5-1. Most frequency allocations above 100 GHz contain absorption lines of important atmospheric trace chemical compounds.

TABLE 5-1

**Frequency bands and bandwidths of scientific interest
for satellite passive sensing below 1 000 GHz***

Allocated frequency band (GHz)	Allocated and {desired} bandwidth (MHz)	Main measurements
1.37-1.427	57	Soil moisture, salinity, ocean surface temperature, vegetation index
2.64-2.7	60	Ocean salinity, soil moisture, vegetation index
4.2-4.4	200	Ocean surface temperature
6.425-7.25 (RR 5.458)	350	Ocean surface temperature (no allocation)
10.6-10.7	100	Rain rate, snow water content, ice morphology, sea state, ocean wind speed
15.2-15.4	200	Water vapour, rain rate
18.6-18.8	200	Rain, sea state, ocean ice, water vapour, snow, ocean wind speed, soil emissivity and humidity
21.2-21.4	200	Water vapour, cloud liquid water
22.21-22.5	290	Water vapour, cloud liquid water
23.6-24	400	Water vapour, cloud liquid water, associated channel for atmospheric sounding
31.3-31.8	500	Sea ice, water vapour, oil spills, clouds, liquid water, surface temperature, reference window for 50-60 GHz range
36-37	1 000	Rain rate, snow, ocean ice, clouds
50.2-50.4	200	Reference window for atmospheric temperature profiling (surface temperature)
52.6-59.3	6 700[1]	Atmospheric temperature profiling (O_2 absorption lines)
86-92	6 000	Clouds, oil spills, ice, snow, rain, reference window for temperature soundings near 118 GHz
100-102	2 000	N_2O, NO
109.5-111.8	2 300	O_3
114.25-116	1 750[1]	CO
115.25-122.25	7 000[1]	Atmospheric temperature profiling (O2 absorption line)
148.5-151.5	3 000	N_2O, Earth surface temperature, cloud parameters, reference window for temperature soundings
155.5-158.5	3 000	Earth and cloud parameters
164-167	3 000	N_2O, cloud water and ice, rain, CO, ClO
174.8-191.8	17 000[1]	N_2O, Water vapour profiling, O_3
200-209	9 000[2]	N_2O, ClO, water vapour, O_3
226-231.5	5 500	Clouds, humidity, N_2O (226.09 GHz), CO (230.54 GHz), O_3 (231.28 GHz), reference window
235-238	3 000[2]	O_3
250-252	2 000[2]	N_2O
275- 285.4	10 400[2]	N_2O, CIO

TABLE 5-1 (*end*)

Allocated frequency band (GHz)	Allocated and {desired} bandwidth (MHz)	Main measurements
296-306	10 000[2]	Wing channel for temperature sounding, OXYGEN, HNO_3, $HOCl$, N_2O, O_3, $O_{17}O$
313-355.6	42 100[2]	Water vapour profiling, cloud, Wing channel for temperature sounding HDO, ClO, HNO_3, H_2O, O_3, $HOCl$, CH_3Cl, $O^{18}O$, CO, BrO, CH_3CN, N_2O, HCN
361.2-365	3 800[2]	O_3
369.2-391.2	22 000[2]	Water vapour profiling, H_2O
397.2-399.2	2 000	Water vapour profiling
409-411	2 000	Temperature sounding
416-433.46	17 460[2]	Oxygen, temperature profiling, O_2
439.1-466.3	27 200	Water vapour profiling, cloud, HNO_3, H_2O, O_3, N_2O, CO
477.75-496.75	19 000	Oxygen temperature profiling, O_2
497-502	5 000[2]	Wing channel for water vapour profiling, O_3, N_2O, BrO
523-527	4 000[2]	Wing channel for water vapour profiling
538-581	43 000[2]	Water vapour profiling, ClO, H_2O, O_3, HNO_3
611.7-629.7	18 000[2]	Water vapour profiling, oxygen, H_2O, ClO_2, SO_2, HNO_3, BrO, CH_3CN, $(H^{37}Cl)$, H_2O_2, $HOCl$, O_3, HO_2, $H^{35}Cl$, CH_3Cl, $O^{18}O$
634-654	20 000[2]	Wing channel for water vapour profiling, $HOCl$, $H_2^{18}O$, SO_2, ClO, HO_2, BrO, HNO_3, O_3, NO, N_2O
656.9-692 (RR5.565)	35 100[2]	Water vapour profiling, cloud, H_2O, HO_2, ClO, CH_3Cl, CO
713.4-717.4	4 000[2]	O_2
729-733	4 000[2]	HNO_3, $O^{18}O$
750-754	4 000[2]	H_2O
771.8-775.8	4 000[2]	O_2
823.15-845.15	22 000[2]	O_2
850-854 (RR5.565)	4 000[2]	NO
857.9-861.9	4 000[2]	H_2O
866-882	16 000[2]	Cloud, window
905.17-927.17	22 000[2]	H_2O
951-956	5 000[2]	O_2, NO, H_2O
968.31-972.31	4 000[2]	H_2O
985.9-989.9	4 000[2]	H_2O

*   NOTE – For current information on passive sensor frequency allocations, the reader is referred to the Table of Frequency Allocations in Article 5 of the RR. For additional information on the preferred frequencies for passive sensing, the reader is referred to the most recent version of Recommendation ITU-R RS.515.

[1]   This bandwidth is occupied by multiple channels.

[2]   This bandwidth is occupied by multiple sensors.

5.2.2   Observation of Earth's surface features

For the measurement of surface parameters (e.g. water vapour, sea surface temperature, wind speed, rain rate, etc.), the so-called radiometric the radiometric "window" channels must be selected such that a regular

sampling over the microwave spectrum from 1 GHz to 90 GHz is achieved (one frequency/octave, on average). However, highly accurate settings of frequencies, in general, are not required because natural emissions of surface parameters are not strongly frequency dependent. In general, several geophysical parameters contribute at varying levels to the natural emission, which can be observed at a given frequency. This is illustrated by Figs 5-2 and 5-3, which represent the sensitivity of natural microwave emissions to various geophysical parameters depending on frequency. Brightness temperature is a measure of the intensity of radiation thermally emitted by an object, given in units of temperature because there is a correlation between the intensity of the radiation emitted and physical temperature of the radiating body.

5.2.2.1 Observation over ocean surfaces

Remote sensing over ocean surfaces is used to measure many of the same parameters as are measured over land (e.g. water vapour, rain rate, wind speed) as well as parameters that provide information on the state of the ocean itself (e.g. sea surface temperature, ocean salinity, sea ice thickness, etc.).

Figure 5-2 shows the sensitivity of brightness temperature to geophysical parameters over ocean surfaces that:

–   measurements at low frequency, typically around 1.4 GHz, give access to ocean salinity;

–   measurements around 6 GHz offer the best sensitivity to sea surface temperature, but contain a small contribution due to salinity and wind speed which can be removed using measurements around 1.4 GHz and around 10 GHz;

–   the 17-19 GHz region, where the signature of sea surface temperature and atmospheric water vapour is the smallest, is optimum for ocean surface emissivity, which is directly linked to the wind speed near the surface, or to the presence of sea ice. Ocean surface temperature also has some sensitivity to water vapour total content and to liquid clouds;

–   total content of water vapour can be best measured around 24 GHz, while liquid clouds are obtained via measurements around 36 GHz; and

–   five frequencies (around 6 GHz, 10 GHz, 18 GHz, 24 GHz and 36 GHz) are necessary for determining the dominant parameters.

FIGURE 5-2

Sensitivity of brightness temperature to geophysical parameters over ocean surface
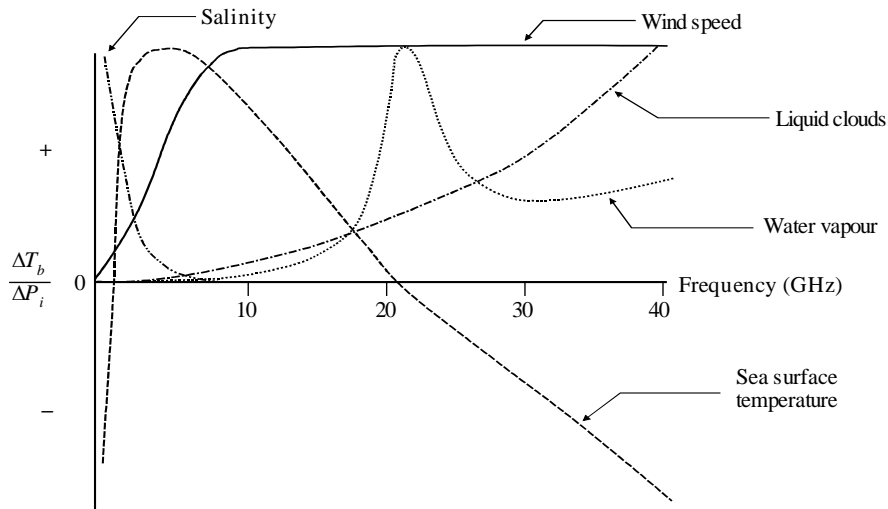
Meteo-05-02

5.2.2.2 Observation over land surfaces

Remote sensing over land surfaces is somewhat more complex due to the high temporal and spatial variability of surface characteristics (from snow/ice covered areas to deserts and tropical rain forest). Moreover, the signal received by the passive sensor has been propagated through a number of different media: basically the soil, perhaps snow and/or ice, the vegetation layer, atmosphere and clouds, and occasionally rain or snow. The second factor to be taken into account is the fact that for each medium, several factors might have an influence on the emitted radiation. For instance, the soil will have a different brightness temperature depending on the actual soil temperature, soil moisture content, surface roughness, and soil texture. Similarly, the vegetation contribution will be related to the canopy temperature and structure through the opacity and single scattering albedo (i.e. the ratio of reflected to incident light). The ways that these factors affect the signal are frequency interdependent. Figure 5-3 depicts the normalized sensitivity as a function of frequency for several key parameters.

Figure 5-3 shows that over land and for an average temperate area, it is necessary to have access to:

–   a low frequency to measure soil moisture (around 1 GHz);

–   measurements around 5 GHz to 10 GHz to estimate vegetation biomass once the soil moisture contribution is known;

–   two frequencies around the water vapour absorption peak (typically 18-19 GHz and 23-24 GHz) to assess the atmospheric contribution;

–   a frequency around 37 GHz to assess cloud liquid water (with use of 18 GHz), and/or vegetation structure (with 10 GHz) surface roughness (with 1 GHz and 5 GHz or 10 GHz).

A frequency at 85 GHz or 90 GHz is useful for rainfall monitoring, but only when all the other contributing factors can be assessed with the lower frequencies.

It has been shown through studies using the scanning multichannel microwave radiometer (SMMR) and the special sensor microwave/imager (SSM/I) that several other variables could be retrieved. These include surface temperature (less accurate than the infrared measurements but with all-weather capabilities) using a channel near 19 GHz when the surface and atmospheric contributions can be estimated.

Snow covered areas are important to monitor and here again the necessity for measurements over several frequencies is crucial. Actually, snow and ice must be distinguished as well as the snow freshness. The related

signal is linked to the structure of the snow layers and the crystal sizes. To retrieve such information it has been shown that several frequencies are required, usually 19 GHz, 37 GHz and 85-90 GHz.

FIGURE 5-3

Sensitivity of brightness temperature to geophysical parameters over land surfaces
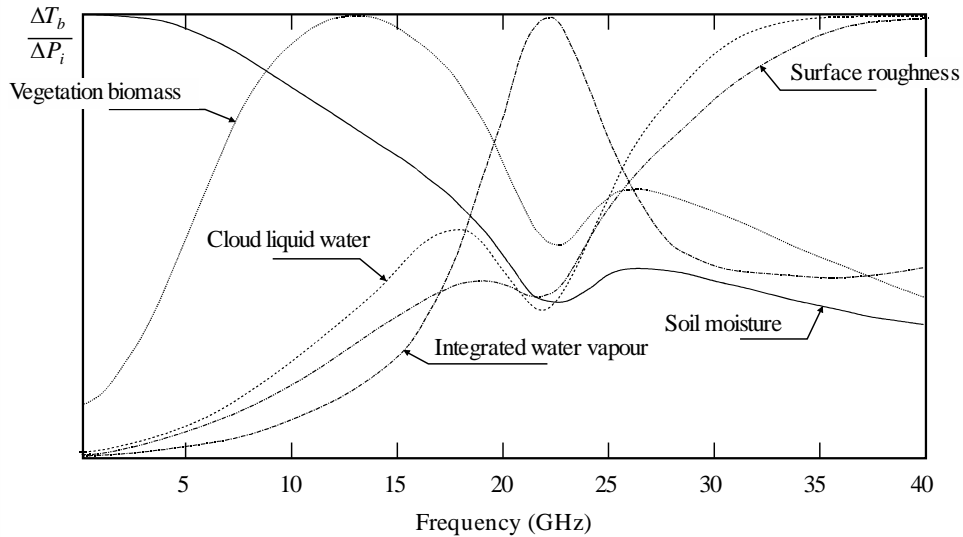
Meteo-05 -03

5.2.2.3 Auxiliary parameters for other remote sensing instruments

Space borne radar altimeters are currently operated on a global basis above ocean and land surfaces, with important applications in oceanography and climatology (see § 5.2.3). In order to remove refraction effects due to atmosphere, the utilization of highly accurate altimetric data acquired around 13.5 GHz requires that they be complemented with a set of auxiliary passive measurements around 18.7 GHz, 24 GHz and 36 GHz.

To be able to separate the different contributions to the signals measured by a satellite, it is essential to have simultaneous access to measurements made at a minimum of five different frequencies.

5.2.3 Performance parameters

Passive sensors are characterized by their radiometric sensitivity and their geometric resolution.

5.2.3.1 Radiometric sensitivity

This parameter is generally expressed as the smallest temperature differential, ΔT_e that the sensor is able to detect. ΔT_e is given by:

$$\Delta T_e = \frac{\alpha T_s}{\sqrt{B\tau}} \qquad K \tag{5-1}$$

where:

B: receiver bandwidth (Hz)

τ: integration time (s)

α: receiver system constant (depends on the configuration)

T_s: receiver system noise temperature (K).

5.2.3.2 Radiometer threshold ΔP

This is the smallest power change that the passive sensor is able to detect. ΔP is given by:

$$\Delta P = k\Delta T_e\, B \qquad \text{W} \tag{5-2}$$

where:

$$k = 1.38 \times 10^{-23}\ \text{(J/K):} \qquad \text{Boltzmann's constant.}$$

ΔP above is computed using ΔT_e and is used in determining the maximum allowable interference that a sensor can tolerate without degrading measurements. In the future, T_s will decrease as well as ΔT_e (see equation (5-1)). Therefore, for the purpose of protecting passive sensor operations in the future, ΔP must be computed using a reasonable foreseen ΔT_e rather than the ΔT_e of current technology. In the same manner, the integration time, τ, will likely increase as remote sensing technology develops further (e.g. the so-called "pushbroom" concept). Therefore, the integration time must also be chosen based on reasonable future expectations.

5.2.3.3 Geometric resolution

In the case of two-dimensional measurements of surface parameters, it is generally considered that the –3 dB aperture of the antenna determines the transversal resolution. In the case of three-dimensional measurements of atmospheric parameters, the longitudinal resolution along the antenna axis must also to be considered. This longitudinal resolution is a complex function of the frequency-dependent characteristics of the atmosphere and the noise and bandwidth performance of the receiver.

5.2.3.4 Integration time

Radiometric receivers sense the noise-like thermal emissions collected by the antenna and the thermal noise of the receiver. By integrating the received signal, the random noise fluctuations can be reduced and accurate estimates can be made of the sum of the receiver noise and external thermal emission noise power. The integration time is simply the amount of time it takes the receiver to integrate the received signal. The integration time is also an important parameter for passive remote sensing, which results from a complex trade-off taking into account in particular the desired geometric resolution, the scanning configuration of the sensor, and its velocity with respect to the scene observed.

5.2.4   Typical operating conditions of passive sensors

Passive spaceborne sensors are deployed essentially on two complementary types of satellite systems: low earth-orbiting satellites and geostationary satellites.

5.2.4.1 Low Earth-orbiting satellites

Systems based on satellites in low, sun-synchronous (i.e. an orbit where the satellite passes over any given point of the Earth's surface at the same local solar time), polar orbits are used to acquire high-resolution environmental data on a global scale. The nature of such orbits limits the repeat rate of measurements. A maximum of two global coverages at 12-hour intervals are obtained daily, with a single satellite. Passive radiometers operating at frequencies below 100 GHz are currently flown only on low-orbiting satellites. This is essentially due to the difficulty of obtaining adequate geometric resolution at relatively low frequencies from higher orbits; however, this may change in the future.

5.2.4.2 Geostationary satellites

Systems involving satellites in geostationary orbit are used to gather low to medium resolution data on a regional scale. The repeat rate of measurements is limited only by hardware technology. Typically, data for one region is collected approximately every 30 min.

5.2.5   Main technical characteristics

Most passive microwave sensors designed for imaging the Earth's surface features use a conical scan configuration (see Fig. 5-4) centred on the nadir (i.e. the point directly below the satellite) direction, because

it is important, for the interpretation of surface measurements, to maintain a constant ground incidence angle along the entire scan lines. The geometry of conically scanned instruments is described in Fig. 5-4.

FIGURE 5-4

Typical geometry of conically scanned passive microwave radiometers

Meteo-05-04
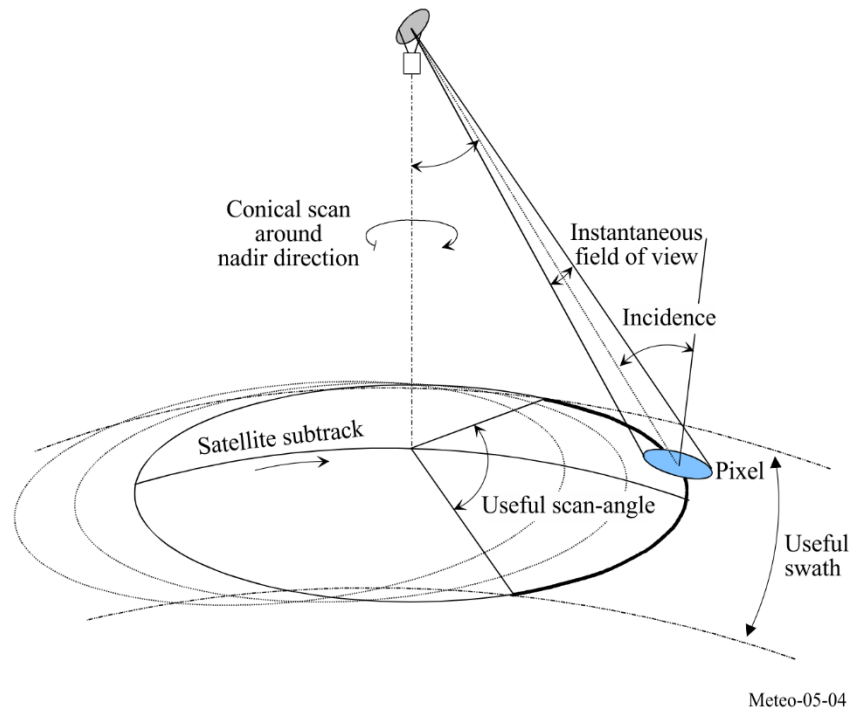
The following are typical geometric characteristics (for 803 km altitude):

– ground incidence angle around 55°

– half-cone angle 46.7° with reference to the nadir direction

– swath width: 1 600 km (limited by the scanning configuration), enabling two complete coverage's to be achieved daily by one instrument, at medium and high latitudes

– pixel size varies with frequency and antenna size, typically from 50 km at 6.9 GHz to 5 km at 89 GHz (based on 2 m effective antenna diameter) and

– scanning period and antenna feed arrangement are chosen in order to ensure full coverage and optimal integration time (and therefore radiometric resolution) at all measured frequencies, at the expense of hardware complexity.

Non-scanning nadir looking instruments may also be used to provide auxiliary data for particular applications, given the removal of atmospheric effects from radar-altimeter measurements. In order to ease their accommodation on board satellites, interferometric techniques are being developed, essentially to improve spatial resolution at low frequencies. Such sensors will use fixed arrays of small antennas instead of large scanning antennas.

A "push-broom" (along track) sensor is a type of sensor system that consists of a line of sensors arranged perpendicular to the flight direction of the spacecraft as illustrated in Fig. 5-5. Different areas of the surface are detected as the spacecraft flies forward. The push-broom radiometer is a purely static instrument with no moving parts. The major feature of the push-broom radiometer is that all of the pixels in a scan line are acquired simultaneously and not sequentially as with mechanically scanned sensors, enabling this type of sensor to significantly increase the achievable radiometric resolution. Push-broom sensors can be used for a variety of

applications including measurements of temperature profiles of the atmosphere, soil moisture and ocean salinity.

FIGURE 5-5

Typical geometry of pushbroom passive microwave radiometers
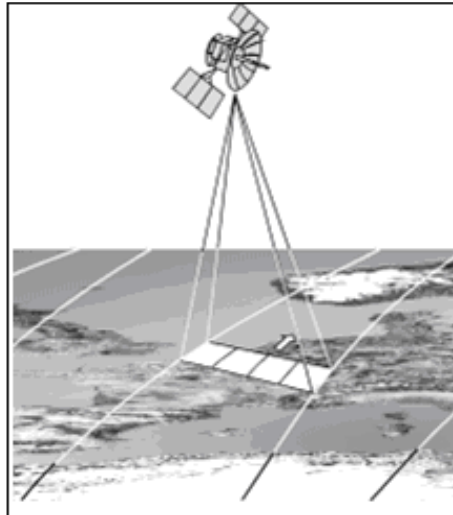
Meteo-05 -05

5.2.6   Performance and interference criteria

The performance and interference criteria for spaceborne passive sensors operating in the EESS are contained in Recommendation ITU-R RS.2017.

5.2.7   Three-dimensional measurement of atmospheric parameters

The electromagnetic spectrum contains many frequency bands where, due to molecular resonances, absorption mechanisms by certain atmospheric gases are taking place (see Fig. 5-1). Frequencies at which such phenomena occur characterize the gas (e.g. O_2, O_3, H_2O, ClO, etc.). The absorption coefficient depends on the nature of the gas, on its concentration, and on its temperature. Combination of passive measurements around these frequencies can be performed from spaceborne platforms to retrieve temperature and/or concentration profiles of absorbing gas. Of particular significance to passive remote sensors operating below 200 GHz are the oxygen resonance frequencies between 50 GHz and 70 GHz, at 118.75 GHz, and the water vapour resonance frequency at 183.31 GHz.

Absorbing gas at wavelength λ radiates energy (at the same frequency) at a level that is proportional to its temperature T and to its absorption ratio $\alpha = f(\lambda)$. This is governed by the relationship given in equation (5-3):

$$l = \alpha \cdot L \qquad (5\text{-}3)$$

where:

l: spectral brightness of the gas at temperature T

$L = 2 \cdot k \cdot T/\lambda^2$:   spectral brightness of the black body at T (W/(m$^2 \cdot$ sr $\cdot$ Hz))

$k = 1.38 \times 10^{-23}$:   Boltzman's constant (J/K)

α: characterizes the gas (O_2, CO_2, H_2O, O_3, etc.).

Two atmospheric gases, CO_2 and O_2, play a predominant role in passive sensing for meteorology because their concentration and pressure in the atmosphere (two parameters which determine the absorption ratio α) are

almost constant and known all around the globe. It is therefore possible to retrieve atmospheric temperature profiles from radiometric measurements at various frequencies in the appropriate absorption bands (typically in the infrared region around 15 μm for CO_2, and in the microwave region around 60 GHz and 118.75 GHz for O_2).

Radiometric measurements in the specific absorption bands of other radioactively and chemically important atmospheric gases of variable and unknown concentration (H_2O, O_3, CH_4, ClO, etc.) are also collected. But in this case, the knowledge of atmospheric temperature profiles is mandatory in order to retrieve the unknown vertical concentration profiles of these gases.

5.2.7.1 Passive microwave atmospheric vertical sounders

Atmospheric sounding is a measurement of vertical distribution of physical properties of a column of the atmosphere such as pressure, temperature, wind speed, wind direction, liquid water content, ozone concentration, pollution, and other properties. Vertical atmospheric sounders (i.e. instruments that take atmospheric sounding measurements) are nadir-looking sensors, which are used essentially to retrieve vertical atmospheric temperature and humidity profiles. They use frequency channels carefully selected within the absorption spectra of atmospheric O_2 and H_2O. Detailed absorption spectra in the vicinity of their main resonance frequencies below 200 GHz are shown in Figs 5-6 to 5-8. Note the very important variability of the water vapour absorption spectrum around 183 GHz, depending on climatic zone and on local weather conditions.

FIGURE 5-6

O_2 absorption spectrum along a vertical path around 60 GHz
(multiple absorption lines)

Passive sensors requirements in O_2 absorption spectrum around 60 GHz
(U.S. standard atmosphere - Absorption model: Liebe, 1993)

Meteo-05-06
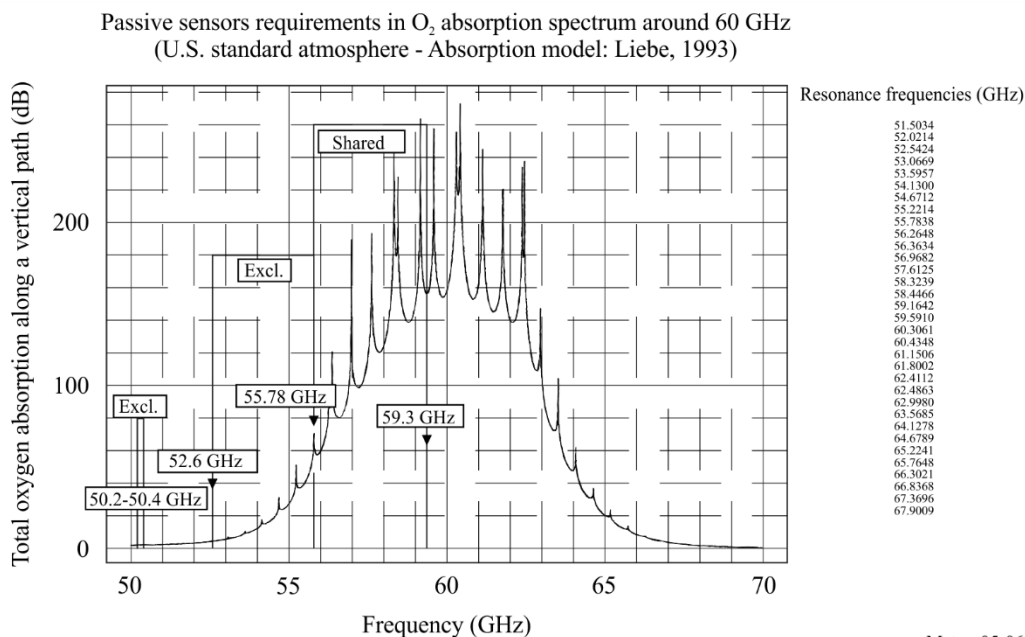
NOTE – Figure 5-6 also depict the position and the EESS allocations and their status between 50 and 60 GHz (50.2-50.4 GHz (exclusive), 52.6-55.78 GHz (exclusive) and 55.78-59.3 GHz (shared)).

FIGURE 5-7

**O₂ absorption spectrum along a vertical path around 118.75 GHz
(one unique absorption line)**

US standard atmosphere 76, Liebe, 1993

Meteo-05 -07
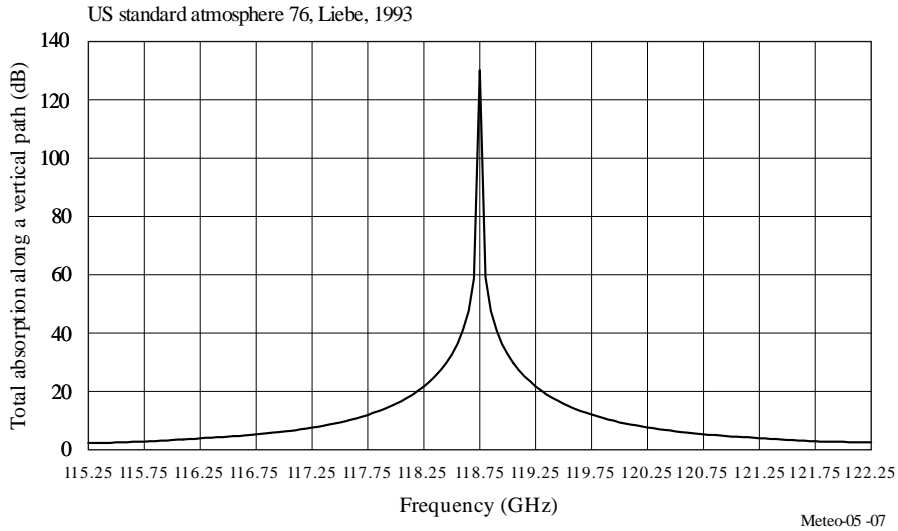
FIGURE 5-8

Water vapour absorption spectrum along a vertical path around 183.31 GHz

Meteo-05 -08
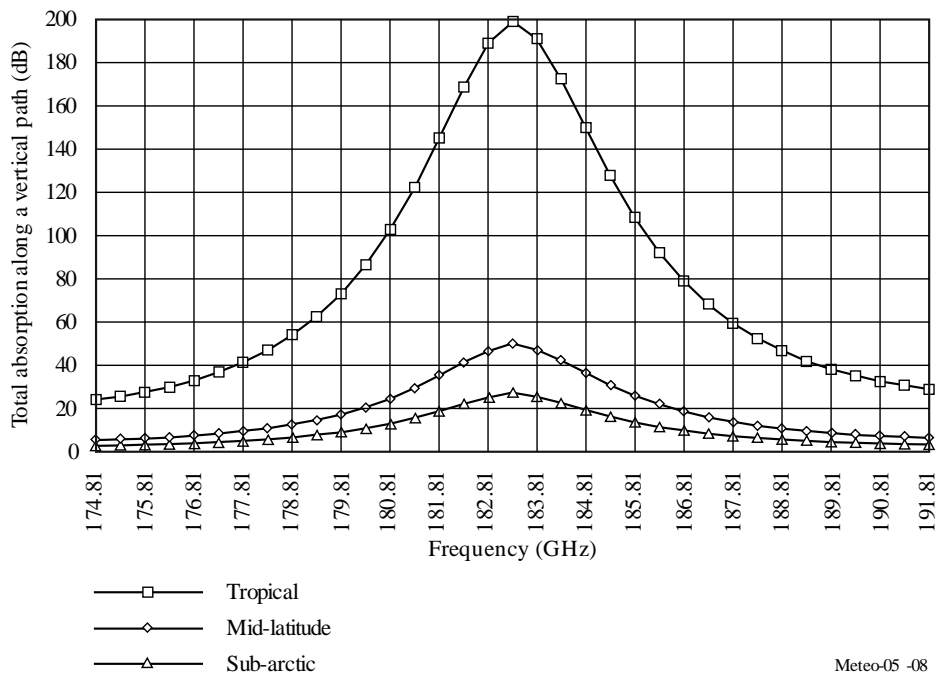
5.2.7.2 Mechanism of vertical atmospheric sounding

In the case of vertical atmospheric sounding from space, the radiometer measures at various frequencies (infrared (IR) or microwave) the total contribution of the atmosphere from the surface to the top.

Each layer (characterized by its altitude) radiates energy proportionally to its local temperature and absorption ratio. The upward energy (in direction of the radiometer) is partly absorbed by the upper layers and in turn, the layer partly absorbs upwards emissions from the lower layers.

Integration of the radiative transfer equation along the path from Earth's surface to the satellite reflects this mechanism, and results in a weighting function which describes the relative contribution of each atmospheric layer, depending on its altitude, and which represents also the longitudinal (vertical) resolution of the sensor.

The peak of the weighting function may occur at any altitude, and depends on the absorption ratio at the frequency considered. At a frequency where the absorption is low, the peak is near the earth's surface. At a frequency where the absorption is high, the peak is near the top of the atmosphere. A sounder incorporates several frequency channels (see Fig. 5-9 for example). They are extremely carefully selected within the absorption band, covering a wide range of absorption levels in order to obtain the best atmospheric samples from the surface up to stratospheric altitudes.

Typical weighting functions for a microwave temperature sounder operating in the 60 GHz band are shown in Fig. 5-9.

FIGURE 5-9

Typical weighting functions for a microwave temperature sounder operating near GHz

Approximative center frequencies (including stratospheric channels)

Channel 1: 23.8 GHz (total Wv)
Channel 2: 31. 4 GHz (window)
Channel 3: 50.3 GHz
Channel 4: 52.8 GHz
Channel 5: 53.6 GHz
Channel 6: 54.4 GHz
Channel 7: 54.9 GHz
Channel 8: 55.5 GHz (tropopause)
Channels 9 to 14: 56.9 to 57.7 GHz
Channels 16 to 21: 60.3 to 61.3 GHz
(alternatively 58.2 to 59.3 GHz)
Channel 15: 89 GHz (liquid water)

Meteo-05 -09

In addition, the particular importance of Channels 1 (23.8 GHz), 2 (31.5 GHz), and 15 (90 GHz) (not shown in Fig. 5-9 above) is to be highlighted. These are auxiliary channels, which play a predominant role in the retrieval process of measurements performed in the O_2 absorption spectrum. As such, they must have similar geometric and radiometric performances and must receive similar protection against interference.

–   Channel 1 is close to a H_2O absorption peak. It is used to retrieve the total water vapour content along the line of sight, and to determine the corrections, which are necessary in the other channels.

–   Channel 2 has the lowest cumulated effects due to oxygen and water vapour. It is the optimum window channel to see the Earth's surface, and is the reference for the other channels.

–   Channel 15 can detect atmospheric liquid water and is used to decontaminate the measurements performed in the other channels from the effects of precipitation.

5.2.7.3   Utilization of vertical atmospheric sounding

The vertical temperature and humidity profiles are essentially used as inputs to the numerical weather prediction (NWP) models, which need to be initialized at least every 6 h. Global NWP (worldwide) models are used to produce a 5 to 10 day weather forecast with a geographical resolution of around 10 km. Also, in increasing numbers, there are regional/local models for a fine mesh prediction (few km) on a short-range basis (6 to 48 h). Figure 5-10 shows the global composite of temperature (K) measurements from the AMSU-A passive microwave sensor, containing measurements produced in a time period of about 12 h. The observations include emission and reflection from the surface plus emission from oxygen mostly in the first 5 km above the surface (see Fig. 5-9).

FIGURE 5-10

Global composite of temperature (K) measurements from AMSU-A
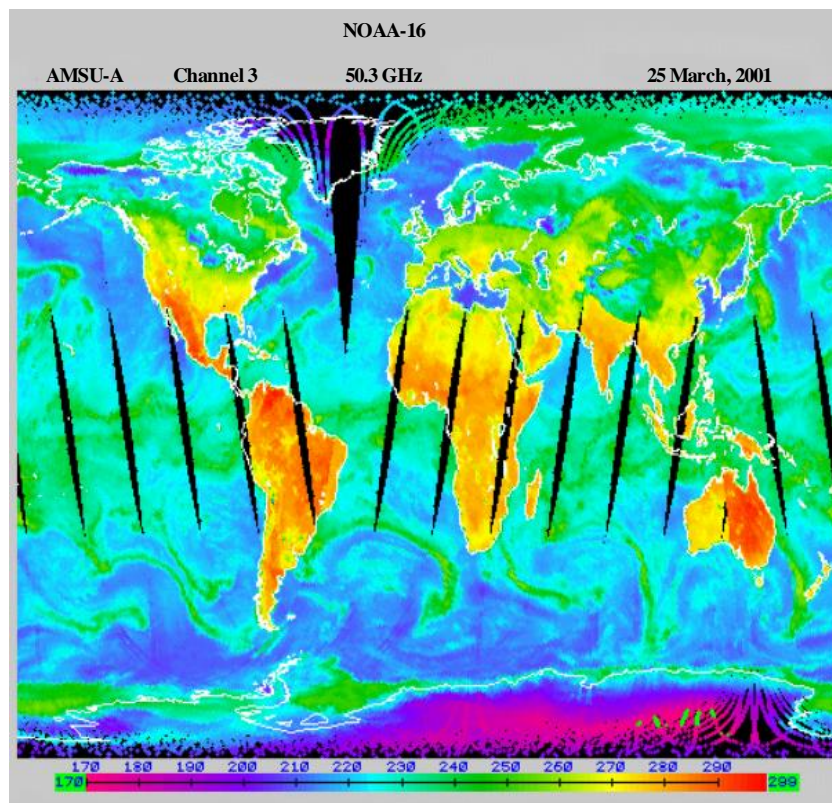
Meteo-05 -10

Figure 5-11 shows the global composite of temperature (K) measurements from AMSU-B. It contains measurements produced in a time period of about 12 h. AMSU-B is a radiometer operated together with AMSU-A to improve the sensing of tropospheric water vapour. At 183 GHz, the radiometer observes high temperature (orange/red colouring) in the tropics and mid-latitudes when the upper parts of the troposphere are dry and the sensor observes nearer the surface, and low brightness temperatures (green) where humidity is high and the radiation originates from higher levels.

The NWP models use partial differential Navier-Stokes equations. Because they simulate highly unstable atmospheric mechanisms, they are extremely sensitive to the quality of the initial three dimensional profiling.

This problem has been described by Lorentz and is now clearly explained by the "chaos theory". To run NWP models, the most powerful super computers are needed.

FIGURE 5-11

Global composite of temperature (K) measurements from AMSU-B
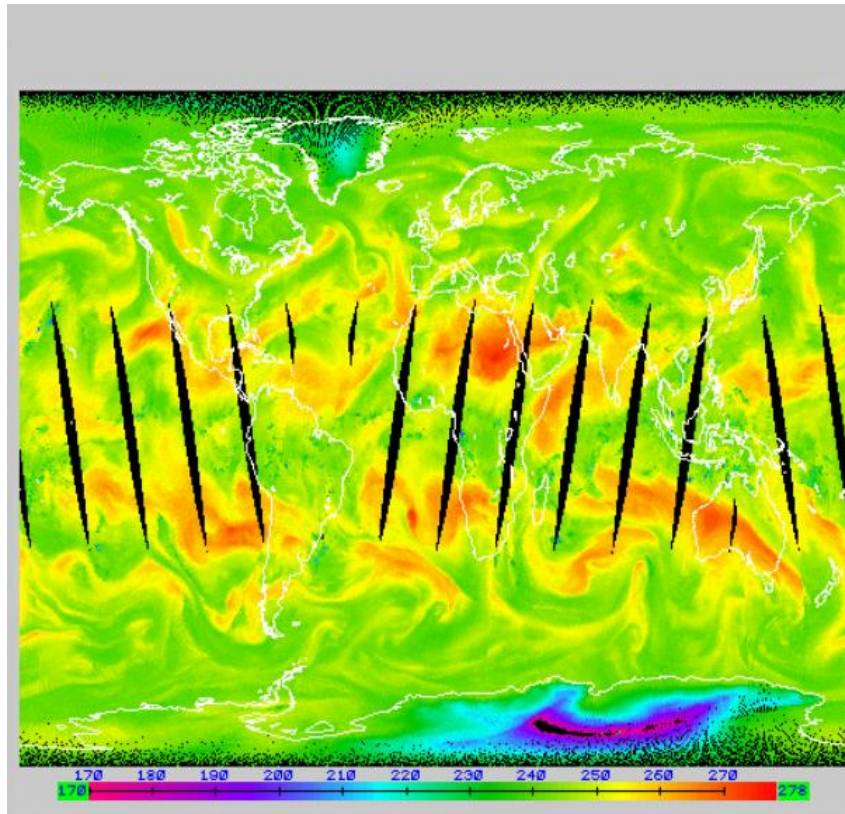
Meteo-05 -11

In order to increase effectiveness of NWP models, it will be necessary to improve and increase the initialization of the models at least every 6 h on a worldwide basis and at a resolution of 50 km for global NWP and 10 km for regional/local NWP. In the future, it will be necessary to get information to allow initialization of the NWP models approximately every three hours.

5.2.7.4 Characteristics of nadir-looking passive sensors operating in the 60 GHz range

Most passive microwave sensors designed for measuring tropospheric/stratospheric parameters, are nadir-looking instruments. They use a cross-track mechanical (current) or push-broom (future) scanning configuration in a plane normal to the satellite velocity containing the nadir direction. This configuration provides optimum field-of-view (FOV) and optimum average quality of data. Typical characteristics of temperature sounders working around 60 GHz and operated on board low Earth orbiting satellites are given in Table 5-2.

TABLE 5-2

Typical characteristics of microwave vertical sounders in the 60 GHz frequency range

Characteristic	Mechanical scanning (current)	Push-broom scanning (future)
Channel bandwidth (MHz)	400	15
Integration time (s)	0.2	2.45
Antenna diameter (cm)	15	45
3 dB points IFOV (degrees)	3.3	1.1
Cross-track FOV (degrees)	±50	±50
Antenna gain (dBi)	36	45
Far lobes gain (dBi)	−10	−10
Beam efficiency (%)	> 95	> 95
Radiometric resolution (K)	0.3	0.1
Swath-width (km)	2 300	2 300
Nadir pixel size (km)	49	16
Number of pixels/line	30	90

5.2.7.5 Passive microwave limb sounders

Microwave limb sounders (MLSs), which observe the atmosphere in directions tangential to the atmospheric layers, are used to study low to upper atmosphere regions, where the intense photochemistry activities may have a heavy impact on the Earth's climate. Major features of tangential limb emission measurements are the following:

– the longest path is used, which maximizes signals from low-concentration atmospheric minor constituents, and renders possible soundings at high altitudes;

– the vertical resolution is determined by the radiative transfer through the atmosphere and by the vertical field of view of the antenna. A typical example is shown in Fig. 5-12;

– the horizontal resolution normal to the line of sight is determined principally by the horizontal field of view of the antenna and the smearing due to the satellite motion;

– the horizontal resolution along the line of sight is principally determined by the radiative transfer through the atmosphere;

– the space background is optimum for calibration of emission measurements; and

– limb measurements are extremely vulnerable to interference caused by inter-satellite links.

Microwave limb sounders were first launched in 1991, and perform the following functions:

– scan the atmosphere vertically in the 15-120 km altitude range, in two side-looking orthogonal directions;

– typical vertical resolution for profile measurements (weighting functions width at half value) is about 3 to 6 km, as shown on Fig. 5-12;

– typical horizontal resolution is 30 km across and 300 km along the direction of observation;

– complete profiles are obtained in less than 50 s; and

– observes thermal limb emission in five microwave spectral regions (see Table 5-3).

FIGURE 5-12

Microwave limb sounding vertical weighting functions (based on a 1.6 m antenna at a 600 km altitude)

Meteo-05 - 12
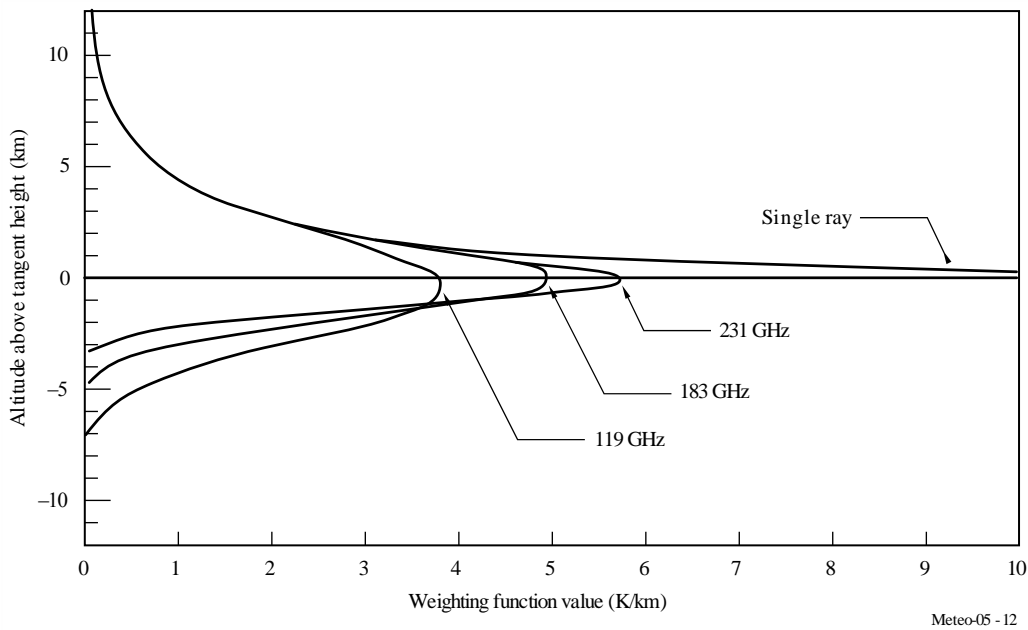
TABLE 5-3

Example measurement objectives of typical microwave limb sounders and spectral regions

Geophysical parameter	Spectral region (GHz)	Altitude (km)	Root mean square noise (interval time)
Atmospheric pressure	50-60	30-70	1% (2 s)
Wind velocity		70-110	2-10 m/s (10 s)
Temperature	119	20-100	0.5-3 K (2 s)
O_2		80-120	3×10^{-3} v/v (2 s)
Magnetic field		80-110	0.3-1 m Gauss (10 s)
H_2O	183	15-90	1×10^{-7} v/v (2 s)
ClO		20-40	2×10^{-10} v/v (10 s)
O_3	205	15-90	1×10^{-8} v/v (2 s)
H_2O_2		20-50	9×10^{-10} v/v (10 s)
O_3	231	15-90	1×10^{-8} v/v (2 s)
CO		15-100	1×10^{-7} v/v (10 s)

The new generation of microwave limb sounders measure lower stratospheric temperature and concentrations of H_2O, O_3, ClO, BrO, HCl, OH, HO_2, HNO_3, HCN, and N_2O, for their effects on, and diagnoses of, ozone depletion, transformations of greenhouse gases, and radiative forcing of climate change. MLS also measures upper tropospheric H_2O, O_3, CO, and HCN for their effects on radiative forcing of climate change and for diagnoses of exchange between the troposphere and stratosphere.

Microwave limb sounders observe the details of ozone chemistry by measuring many radicals, reservoirs, and source gases in chemical cycles that destroy ozone. This set of measurements will provide stringent tests on understanding of global stratospheric chemistry, will help explain observed trends in ozone, and can provide early warnings of any changes in the chemistry of this region.

The original microwave limb sounders demonstrated the capability of measuring upper tropospheric water vapour profiles. This knowledge is essential for understanding climate variability and global warming but which previously has been extremely difficult to observe reliably on a global scale.

Future microwave limb sounders may observe additional atmospheric chemistry components and species at other frequencies.

5.2.7.6 Vulnerability to interference of passive microwave sounders

Passive sensors integrate all natural (wanted) and man-made (unwanted) emissions. They cannot, in general, differentiate between these two types of signals because the atmosphere is a highly unstable medium with rapidly changing characteristics, both spatially and temporally. A particular problem for passive sensors is the presence of large numbers of low power emitters within the sensor's measurement area. Among such low power emitters are ultra-wide band (UWB) devices, industrial, scientific and medical (ISM) applications and short range devices (SRD). The situation tends to be more and more critical with the increased density of such terrestrial active devices and instances of harmful interference have already been reported.

The passive sensor measurements are therefore extremely vulnerable to interference, even at very low power levels, which may have very serious detrimental consequences:

– It has been demonstrated that as few as 0.1% of contaminated satellite data samples could be sufficient to generate unacceptable errors in numerical weather prediction forecasts, thus destroying confidence in these unique all weather passive measurements.

– The systematic deletion of data where interference is likely to occur (should it be detectable) may cause vital indications of rapidly developing potentially dangerous storms may to be missed and render impossible the realization of new developing weather systems.

– If interference is at a low enough power level that it is not detected, which is more than likely, corrupted data will be mistaken for valid data and the conclusions derived from the analysis incorporating these corrupted data will be seriously flawed.

– For climatological studies and particularly for "global change" monitoring, interference may lead to misinterpretation of climate signals.

Recommendation ITU-R RS.2017 provides the required radiometric performance and the permissible interference level under which the required performance can be met.

5.3   Active sensors

5.3.1   Introduction

The purpose of this section is to describe the radio spectrum frequency needs of the spaceborne active sensors, and in particular, those sensors used in the monitoring of meteorological phenomena. The intent is to present the unique types of sensors and their characteristics which determine their individual frequency needs; to present performance and interference criteria necessary for compatibility studies with other services in the frequency bands of interest and to present the status of current compatibility studies of spaceborne active sensors and other services, along with any issues or concerns.

There are five key active spaceborne sensor types addressed in this Handbook:

Type 1: *Synthetic aperture radars (SAR)* – Sensors looking to one side of the nadir track, collecting a phase and time history of the coherent radar echo from which typically can be produced a radar image of the Earth's surface.

Type 2: *Altimeters* – Sensors looking at nadir, measuring the precise time between a transmit event and receive event, to extract the precise altitude of the Earth's ocean surface, including coastal and inland waters.

Type 3: *Scatterometers* – Sensors looking at various aspects to the sides of the nadir track, using the measurement of the return echo power variation with aspect angle to determine the wind direction and speed on the Earth's ocean surface, including coastal and inland waters. Backscatter is also used to look at all land surfaces, providing Earth's surface conditions such as soil moisture and rain over land.

Type 4: *Precipitation radars* – Sensors scanning perpendicular to nadir track, measuring the radar echo from rainfall, to determine the rainfall rate over the Earth's surface and three-dimensional structure of rainfall.

Type 5: *Cloud profile radars* – Sensors looking at nadir, measuring the radar echo return from clouds, to determine the cloud reflectivity profile over the Earth's surface.

The characteristics of the five key types of active spaceborne sensors are summarized in Table 5-4.

TABLE 5-4

Active spaceborne sensor characteristics

Characteristic	**Sensor types**				
	SAR	**Altimeter**	**Scatterometer**	**Precipitation radars**	**Cloud profile radars**
Viewing geometry	Side-looking at 10°-55° off nadir	Nadir-looking Multi incidence looking	– Three/six fan beams in azimuth – One or more conically scanning beams	Scanning across-track around Nadir-	Nadir-looking
Footprint/-dynamics	– Fixed to one side – ScanSAR – Spotlight	Fixed at nadir Multi incidence looking	– Fixed in azimuth – Multiple conically scanning beams	Scanning across nadir track	Fixed at nadir
Antenna beam	Fan beam	Pencil beam	– Fan beams – Pencil beams	Pencil beam	Pencil beam
Radiated peak power (W)	1 500-8 000	20	100-5 000	600	1 000-1 500
Waveform	Linear FM pulses	Linear FM pulses	Interrupted CW or short pulses(ocean) or linear FM pulses (land)	Short pulses	Short pulses
Bandwidth	20-1200 MHz	320/500 MHz	5-80 kHz (ocean) or 1-4 MHz (land)	14 MHz	300 kHz
Duty factor (%)	1-30	46	31 (ocean) or 10 (land)	0.9	1-14
Service area	Land/coastal/ocean	Ocean/ice/coastal/Inland water	Ocean/ice/land/coastal	Land/ocean	Land/ocean
Typical frequency bands	1.3 GHz, 5 GHz, 9 GHz and 36 GHz	5 GHz, 13 GHz and 36 GHz	1.3 GHz, 5 GHz and 13 GHZ	36 GHz and 78 GHz	94 GHz, 138 GHz and 238 GHz

5.3.2   Synthetic aperture radars (SARs)

SARs provide radar images of the Earth's surface. The choice of RF centre frequency depends on the Earth's surface interaction with the EM field. The RF bandwidth affects the resolution of the image pixels. In Fig. 5-13a), the chirp pulse is shown, and the corresponding RF bandwidth is shown below. The range resolution is equal to $c/2/(BW \sin \theta)$, where c is the velocity of light, BW is the RF bandwidth, and θ is the incidence angle. To obtain 1 m range resolution at 30° incidence angle, for instance, the RF bandwidth should be 300 MHz. Many SARs illuminate the swath off to one side of the velocity vector as shown in Fig. 5-13b). Any interference sources within the illuminated swath area will be returned to the SAR receiver and degrade the image pixel quality. The allowable image pixel quality degradation determines the allowable interference level. Figure 5-14 shows a SAR image taken of the Dead Sea between Israel and Jordan.

FIGURE 5-13

Chirp spectrum and SAR illumination swath
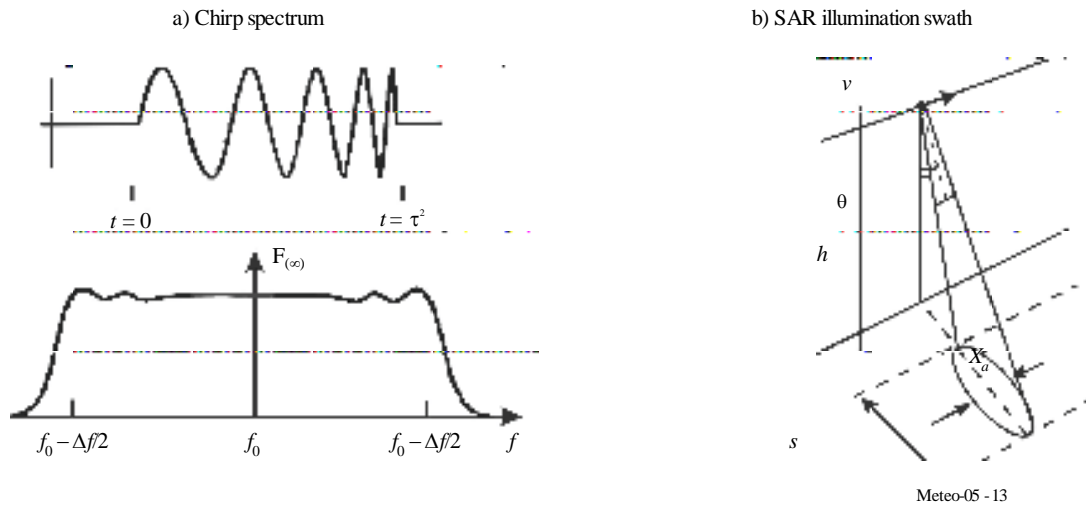
Meteo-05 - 13

FIGURE 5-14

SAR image of the Dead Sea along the West Bank between Israel and Jordan

Meteo-05 - 14

5.3.3   Altimeters

Altimeters provide measurements of the altitude of the Earth's ocean surface. Figures 5-15, 5-16a) and 5-16b) are an illustration of a satellite altimeter and its typical measurement accuracy. The choice of RF centre frequency depends on the ocean surface interaction with the EM field. Dual frequency operation allows ionospheric delay compensation. For instance, the use of frequencies around 13.6 GHz and 5.3 GHz illustrates one possible dual frequency arrangement. The wide RF bandwidth affects the height measurement accuracy. The time difference accuracy Δt is inversely proportional to BW, where BW is the RF bandwidth. The allowable height accuracy degradation determines the allowable interference level. Some satellite altimeters have measured ocean topography to an accuracy of 4.2 cm. The allowable performance degradation prescribed by Recommendation ITU-R RS.1166-4 is 4%.

FIGURE 5-15

Microwave satellite altimeter
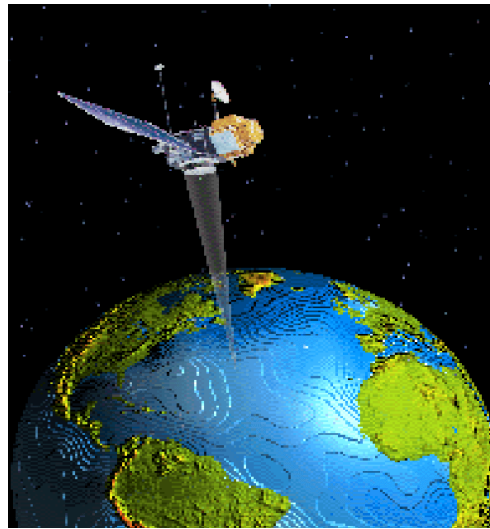
Meteo-05 - 15

FIGURE 5-16

Illustration of altimeter return and spreading of return pulse

a) Illustration of altimeter return   b) Spreading of return pulse
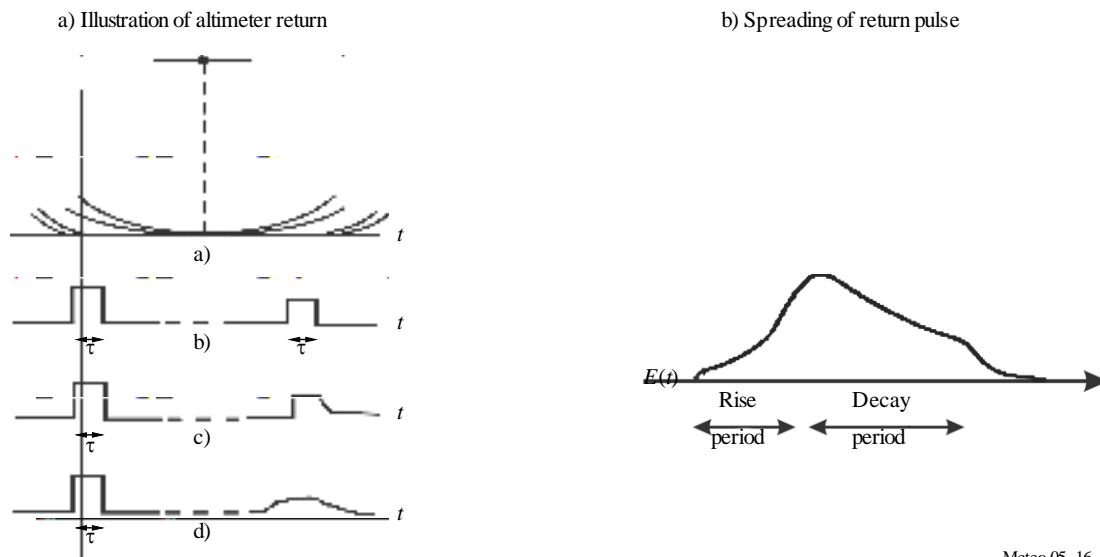
Meteo-05 -16

5.3.4   Scatterometers

Scatterometers mainly provide measurements of the wind direction and speed over the Earth's ocean surface and sea ice extent and characteristics. The choice of RF centre frequency depends on the ocean surface interaction with the EM field and its variation over aspect angle. Figure 5-17 shows the variation of backscatter level with aspect angle relative to the wind velocity vector direction.

FIGURE 5-17

Variation of backscatter with aspect angle
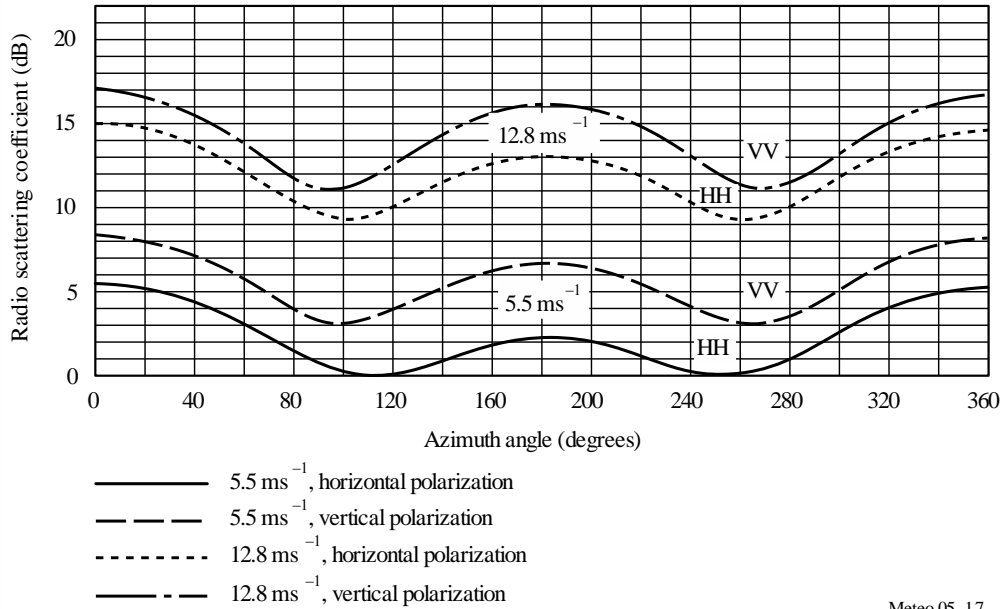
Meteo-05 -17

As shown in Fig. 5-18, a typical scatterometer illuminates the Earth's surface at several different fixed aspect angles. In Fig. 5-19 a scatterometer scanning pencil beam illuminates scans at two different look angles from nadir, and scans 360 degrees about nadir in azimuth. The narrow RF signal bandwidth provides the needed measurement cell resolution.

FIGURE 5-18

Scatterometer fixed footprint
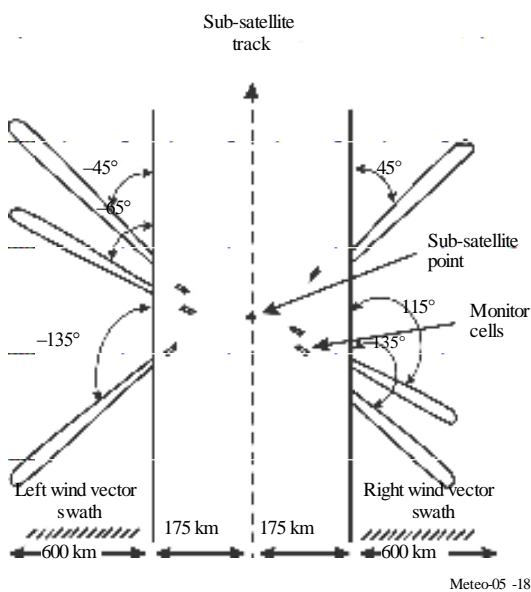
FIGURE 5-19

Scatterometer pencil beam scan
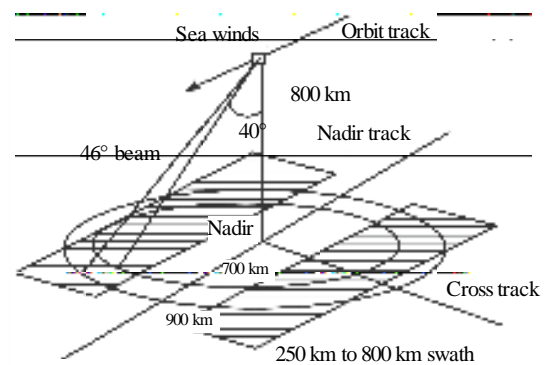
Meteo-05 -18

Meteo-05 - 19

The scatterometer's primary function is to study winds over the oceans, but scientists have devised a way of studying changes in the instrument's radar backscatter to also look at all land surfaces, providing Earth's surface conditions such as soil moisture and rain over land. Figure 5-20 shows an example radar image taken from the NSCAT scatterometer of the Amazon rainforest in South America. The scatterometer's radar was sensitive to conditions on the Earth's surface, such as the type and density of vegetation.

FIGURE 5-20

NSCAT scatterometer radar image of the Amazon rainforest in South America
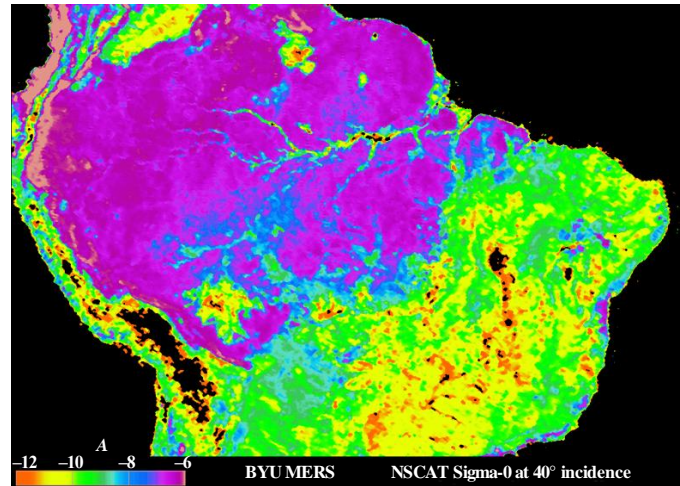
Meteo-05 -20

5.3.5   Precipitation radars

Precipitation radars provide measurements of the precipitation rate over the Earth's surface, typically concentrating on rainfall in the tropics.

The choice of RF centre frequency depends on the precipitation interaction with the EM field. The backscatter cross section of a spherical hydrometeor is:

$$\sigma_b = \pi^5 |K_W|^2 D^6/\lambda^4 = \pi^5 |K_W|^2 Z/\lambda^4 \tag{5-4}$$

where:

$|K_W|^2$:   related to the refractive index of the drop's water

D: diameter of the drop (m)

λ: wavelength of the radar (m)

Z: radar reflectivity factor.

The backscatter increases as the fourth power of the RF frequency.

Figure 5-21 shows an example of a vertical cross section of radar reflectivity factor. The narrow RF signal pulse-width provides the needed measurement range resolution. One example precipitation radar uses a pulse width of 1.6 μs, though the value may vary with other systems. The allowable minimum precipitation reflectivity degradation determines the allowable interference level.

FIGURE 5-21

Synthesized reflectivity from precipitation reflectivity measurements
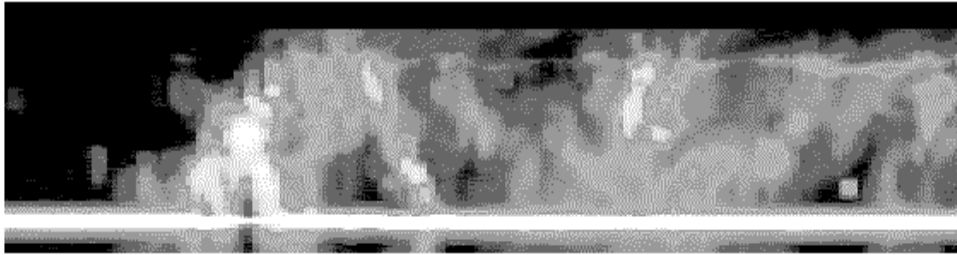
Meteo-05 -21

5.3.6   Cloud profile radars

Cloud profile radars provide a three dimensional profile of cloud reflectivity over the Earth's surface. Figure 5-22 shows a representative backscatter reflectivity versus altitude.

The choice of RF centre frequency depends on the ocean surface interaction with the EM field and its variation over aspect angle.

Equation (5-5) gives the expression for calculation of the return power level of the clouds.

$$\tilde{P} = \frac{\pi^5 10^{-17} P_r G^2 t \, \theta_r^2 \left| K_W \right|^2 Z_r}{6.75 \times 2^{14} (\ln 2) \, r_0^2 \lambda^2 l^2 l_r} \quad \text{mW} \tag{5-5}$$

where:

$\tilde{P}$:   return power level of the clouds (mW)

P_r: radar transmit power (W)

G: antenna gain (numeric)

t :   pulse width (µs)

θ_r: 3 dB antenna beamwidth (degrees)

K_W: dielectric factor of the cloud water content

Z_r: cloud reflectivity factor (mm^6/m^3)

r_0:   range distance (km)

λ: radar wavelength (cm)

l: signal loss due to atmospheric absorption

l_r: radar system loss.

As illustrated by this equation, the return power decreases with the square of the wavelength. Since frequency is inversely proportional to wavelength, the return power increases with the square of the RF frequency. In the case of small particles (Rayleigh regime), the return power increases as the frequency to the power of four since the ratio depends on the relative particle size with respect to the wavelength. The cloud profile radar antennas have very low sidelobes so as to isolate the cloud return from the higher surface return illuminated by the sidelobes.

FIGURE 5-22

Example of cirrus cloud reflectivity

Tropical cirrus observed during transit from Hawaii to New Zealand

Distance (km)

Meteo-05 -22
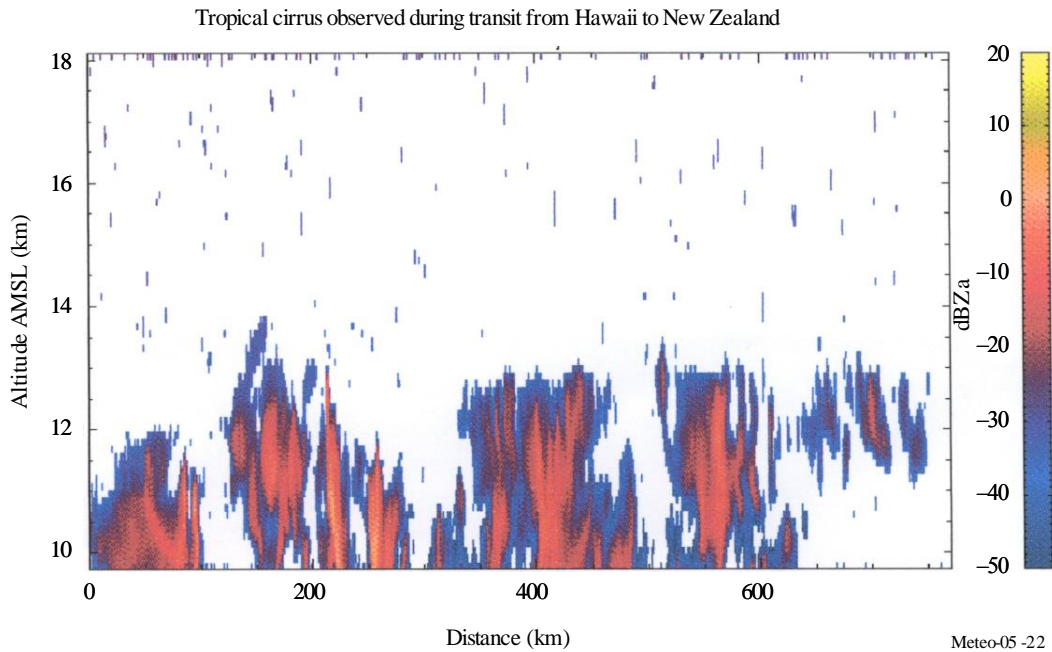
5.3.7   Sensor interference and performance criteria

The criteria for performance and allowable interference are provided in Recommendation ITU-R RS.1166 for the various types of active spaceborne sensors. The recommendation is periodically revised to reflect regulatory modifications, such as a new EESS (active) allocation, and changes in the sensor state-of-the-art that would affect existing criteria for performance and allowable interference.

5.3.8   Power flux-density (pfd) levels

The characteristics of the various types of active spaceborne sensors as shown in Table 5-4 indicate that the transmitted peak power and therefore the power levels received at the Earth's surface will vary significantly in level. Table 5-5 shows the active sensor power flux-density levels at the Earth's surface for some typical sensor configurations.

TABLE 5-5

Typical power flux-density levels at Earth's surface

Parameter	Sensor type				
	SAR	**Altimeter**	**Scatterometer**	**Precipitation radars**	**Cloud profile radars**
Radiated power (W)	1 500	20	100	578	630
Antenna gain (dB)	36.4	43.3	34	47.7	63.4
Range (km)	695	1344	1 145	350	400
pfd (dB(W/m^2))	−59.67	−77.25	−78.17	−46.55	−31.64

CHAPTER 6

OTHER RADIOCOMMUNICATION SYSTEMS FOR METEOROLOGICAL ACTIVITIES

Page

6.1   Introduction

As discussed in Chapter 1, meteorological services need to collect observations from many remote sites, both on land and over the sea. Thus, the meteorological observing system is dependent on many other radiocommunication services in addition to the MetSat, MetAids, radiolocation and EESS services described in the earlier Chapters.

It is also essential that meteorologists disseminate information and warnings to customers with minimal delay, whether in densely populated areas or in remote sparsely populated areas. In addition meteorological services are supplied to support maritime operations and to support aviation operations worldwide. To do so, the dissemination systems for meteorological products utilize a wide range of radiocommunication services.

6.2   Dissemination systems

Dissemination of forecasts is of equal importance to the collection and archiving of weather data. Making these predictions available to the public is a prerequisite to saving lives in order for people to take the steps necessary to protect their lives and property.

A number of specialized radio systems have been developed over the years by which forecasts and other meteorological data are distributed. Among the simplest of these is voice broadcasting. Typically using VHF radio, these systems require minimal equipment to be used by the general public. These systems serve to warn the public of threatened storms, floods, extreme temperatures and other natural and man-made hazards. Enhancements may be provided such as brief data transmissions accessible to deaf persons using special equipment. These systems may also be designed to provide continuous data distribution, or to remain silent until triggered by an alert tone signifying a special event such as foul weather or other imminent hazard. Dissemination systems may be found in the fixed and mobile services, including maritime mobile service. Other dissemination systems operate via radio and television broadcasts (terrestrial and satellite) and on MetSat downlinks.

Over the years, high frequency radio has been used by many administrations to provide weather and warning information to ships at sea and to aircrafts. These systems typically provide voice transmissions and weather facsimile (WEFAX). However, the unreliable nature of HF has caused a transition of many such systems to satellite transmission.

Finally, it should also be noted that the fixed-satellite service systems, through commercial payloads in the C-band ((3 400-4 200 MHz) and the Ku Band (10 700-11 700 MHz), are nowadays used globally to disseminate weather, water and climate related information, including disaster warnings to meteorological agencies and user communities. The use of the C-Band satellites is particularly important in areas where propagation conditions (e.g. heavy rain in tropical and equatorial zones) make the use of any other telecommunication support impractical.

6.3   Hydrological systems

Floods are a natural and inevitable part of life in much of the world, and systems that can aid in predicting their occurrence, location and magnitude have saved many lives and a significant amount of property. Advance knowledge permits the evacuation of vulnerable populations, the construction of levees and dams, and the relocation of such valuable and vulnerable property as can be removed.

As a complement to meteorological radar networks (see Chapter 4) that are nowadays an essential tool in the hydrological process, specific hydrological systems are also typically used to measure precipitation, stream height and the depth of snow pack, all of which are required in the prediction and early warning of flooding. They are also useful in estimating the availability of water resources.

Annual average flood damage in the United States of America alone now approaches 4 billion US dollars. Communities with persistent flood problems and those vulnerable to great losses when flooding does occur are continually seeking ways to minimize these losses. Automated hydrological systems are an attractive solution because of their low cost of operation and because they can enhance the operation of other flood mitigation methods such as reservoir floodgate operation, flood insurance, or floodplain zoning.

An automated hydrological system consists of event-reporting meteorological and hydrologic sensors, radiocommunications equipment, and computer software and hardware. In its simplest form, coded signals are transmitted via the radiocommunications equipment, usually using the VHF or UHF bands under the fixed or mobile services, to a base station, often through repeater sites (see Fig. 6-1). The base station collects these coded signals and processes them into meaningful hydrometeorological information that can be displayed or tied to an alarm system and may notify emergency managers when the preset criteria are exceeded.

FIGURE 6-1

Schematic of a hydrologic system

Hydrological sensors

Raw data

Radio repeater

Receiver

Decoder

Computer

LOCAL DATA COLLECTION
(ALERT SYSTEM)
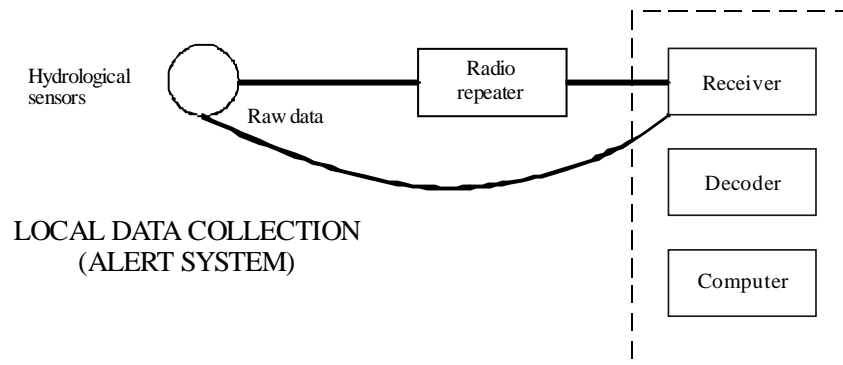
Sensor data processed locally at computer site.
No dedicated communications between other computer processing sites.
Coverage area limited to radio range of sensors and repeaters.

Meteo-06-01

6.4 Radiocommunications for remote meteorological and environment systems

Technical characteristics, including operating frequencies, of these systems vary widely and almost any of the meteorological RF bands may be used. Selection is frequently made based on the necessary bandwidth, which in turn is determined by the type and quantity of information to be carried. Fixed remote systems in meteorology serve a variety of purposes and operate in a number of RF bands. As would be expected from their name, they operate in fixed allocations. Typical uses include:

Voice keying or feeder links used to carry control or data signals to data dissemination transmitter sites, which are often located remotely (e.g. on mountain tops) to maximize their coverage areas.

Radar remoting used to carry radar return signals from the radar itself (frequently located remotely) to the office where data are processed. Operators also use RF for remote control of equipment at the radar site.

Data collection used to convey from remotely-located collection sites to a central repository or processing facility the data collected by hydrological and meteorological sensors used to measure wind, rain, temperature, snow depth, earth tremors (for the detection or prediction of earthquakes), or any number of other natural phenomena.

6.5 Meteorological uses of Global Navigation Satellite Systems (GNSSs)

GPS signals currently transmitted at 1 575.42 MHz (designated L1) and 1 227.6 MHz (designated L2) (and those of GLONASS) are used by meteorologists for the following purposes:

– *Location of mobile meteorological observing platforms:* for example radiosondes carried by weather balloons, dropsondes falling on parachutes, unmanned aircraft carrying meteorological sensors (see Chapter 3), or marine meteorological systems such as ocean buoys.

– *Very accurate synchronization of time*: between remote observing sites, as required for instance by lightning detection systems (see § 6.5).

– *Measurement of total water vapour in the atmosphere*: derived from the phase delay in the GPS signals received by ground based receivers. Computation of total water vapour requires extremely

accurate computations of the position of the various GPS satellites and the timing of the satellite clocks. The position of the ground receiver must also be known very accurately. The GPS receivers are usually installed on a fixed mount suitable for accurate tracking of position on the Earth's surface as well as providing meteorological information. Thus, the measurements may be produced as a byproduct of geodetic/ seismological observations or from sensors deployed specifically by meteorologists. Phase delays introduced in signal transmission through the ionosphere are identified from the differences in the phase delays between the two GPS frequencies, L1 and L2. If the surface pressure and temperature are known, the dry hydrostatic phase delay introduced by the atmosphere can be estimated, and the remaining phase delay is then proportional to the total water vapour along the path to the satellite. The GPS sensor at the surface receives GPS signals from many directions in a short period of time. Thus, it is possible to estimate the total water vapour in the vertical, as well as gradients in total water vapour in the horizontal direction around the sensor. This technique has relevance for atmospheric propagation studies, since it allows a direct measurement of water vapour content along a slant path from the ground receiver to a satellite. See also [Coster *et al.*, 1997].

– *Measurement of temperature and relative humidity as a function of height derived from space-based occultation measurements of the GPS signals:* in this application, a receiver on an independent satellite receives signals from the GPS constellation passing through the atmosphere at grazing incidence to the Earth's surface. The refraction of the GPS signals is measured at a range of heights above the Earth's surface. This allows the refractive index of the air to be derived as a function of height. At upper levels in the neutral atmosphere, relative humidity is very low and the refractive index of air can be assumed to be directly dependent on temperature. At levels closer to the surface below the tropopause, both temperature and partial pressure of water vapour influence the refractive index. The partial pressure of water vapour can be estimated if the temperature is already known from another source. The measurement of meteorological variables derived from this technique will have a better vertical resolution than the output from nadir viewing passive sensing radiometers, see Chapter 5, but will be averaged over relatively long distances in the horizontal. As with the total water vapour measurement, this technique requires very precise timing and knowledge of the position of both satellites. GNSS receivers are planned for the next generation of polar orbiting meteorological satellites.

6.6   Lightning detection systems

The need by operational meteorologists for remote sensing of lightning activity is nowadays an important tool used by operational meteorologists. Customer requirements are developing in conjunction with developments in the use of weather radar and meteorological satellite products, and have a high priority given the need to automate surface weather observations in many developed countries. The reliable operation of these systems has clear links to considerations of public safety on land, sea and air. Provision of an effective forecast service impacts the efficiency of commercial and defence activities. The safety of engineers working on power lines and personnel handling explosive devices are examples of activities that benefit from effective lightning forecasts.

The detection of lightning is a passive activity involving the use of radio receivers to detect wave fronts resulting from lightning. Data from individual detection sites may be distributed by any of the usual means including fixed links, telephone, Internet, etc.

In current operational systems, the position of the lightning flash is either determined by measuring the direction of arrival of the associated spheric (atmospheric wave), or by measuring the time of arrival of the spheric, or a combination of both.

Measurements are required at more than three widely spaced sensing sites. The number of sites used in practice is usually larger than the minimum in order to improve the reliability of the reported locations. Time of arrival systems usually provide more accurate locations than direction finding systems when observing at ranges over several hundred kilometres. This is due to the direction of reception of skywaves sensed at the site, which usually differs slightly from the actual direction of the discharge, and will vary according to the state of the surface layers near the sensing site. Time of arrival systems usually rely heavily on GPS radionavigation signals to achieve the necessary time synchronization at the various sensing sites. All systems rely on cost effective, reliable communications from the remote sites to the central processor. The radio frequency used to

locate lightning activity varies according to the area of monitoring required and the specific purpose of the system.

Very long-range locations at distances of several thousand kilometres are achieved operationally by observing frequencies centred at 10 kHz (2-15 kHz) (see Fig. 6-2), such as the ATDNET system operated by the Metoffice of UK. In this system, the spherics are received at the remote outstations located worldwide with spacings of up to 2 000 km apart. The spherics are Fourier analysed and time stamped at the sensor sites. The timed samples are immediately transmitted back to a central control station where the locations of the lightning discharges are computed from the differences in arrival times at the sites. Low levels of interference can sometimes be countered by using an adjustable notch filter at the affected sensor sites, but widespread and higher levels of interference are extremely detrimental to the operation of the system.

Taking into account the importance of such long-range lightning detection network and the need for a global recognition, a specific allocation to the Meteorological Aids service, limited to passive sensors, was made at WRC-12 in the band 8.3-11.3 kHz.

FIGURE 6-2

Map of lightning data for one day for long range system

11 581 thunderstorm records in this 24 h period
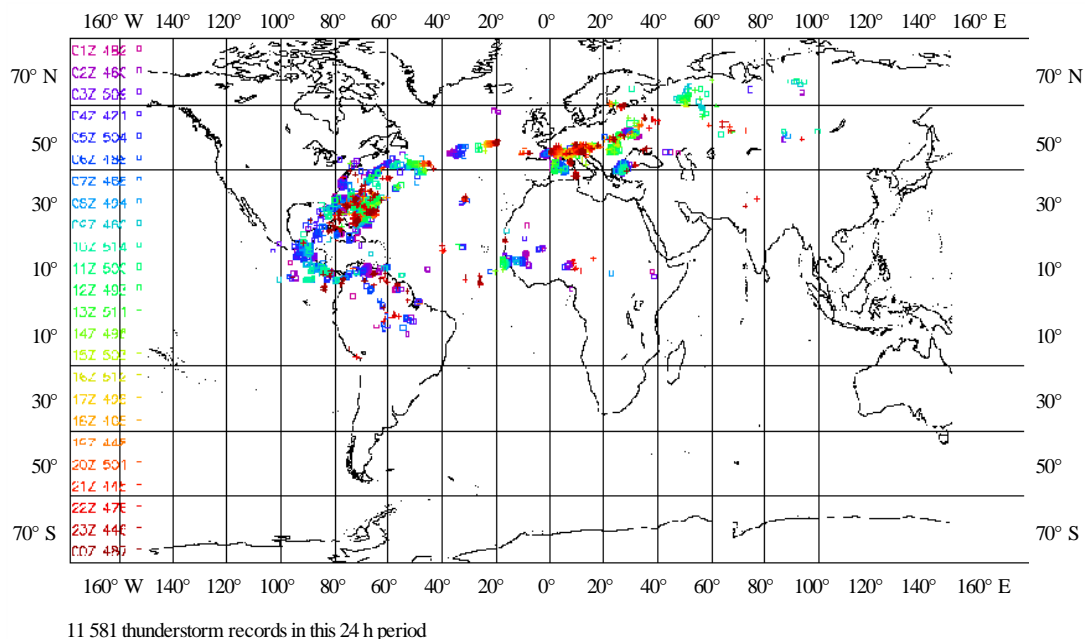
Meteo-06-02

The most widely used operational systems cover a more limited area in detail. In this case, the spherics are observed at higher frequencies centred around 200 kHz (the wideband receivers used are most sensitive in the middle of their range of 1 kHz to 350 kHz), and the sensing sites are usually spaced between 100 km and 400 km apart, depending on whether the emphasis is on cloud-to-ground or cloud-to-cloud flashes. At these higher frequencies, a discharge from the cloud-to-ground can be identified by a pronounced rise in amplitude defining a leading edge to the spheric. The arrival of this leading edge can be accurately timed. The times from the network sites are transmitted to a central processor and used to compute the positions of the discharges. In many cases, the network arrival time differences are operated in conjunction with magnetic direction finding systems installed in earlier years. [Holle and Lopez, 1993] review different lightning detection systems and [Diendorfer *et al.*, 1994] discuss observations from their own network in Austria.

In addition, in some areas it is necessary to observe all the electrical discharges associated with thunderstorm activity, both cloud-to-ground and cloud-to-cloud discharges. This is achieved by observing at very much higher frequencies (63 MHz and 225 MHz are used by the lightning detection and ranging system (LDAR), while the SAFIR (Surveillance et Alerte Foudre par Interférométrie Radioélectrique) system uses 110 to

118 MHz). Figure 6-3 shows the real-time LDAR display. The storms must remain within line-of-sight if all the activity is to be observed. This requires that the ground sensors be located in a short baseline configuration – the sensors need to be 30 km apart, and about 50 m from the ground to fulfil the radar horizon criteria. In practice, however, some operational systems observing cloud-to-cloud activity are operated with the ground sensors further apart, relying on the cloud-to-ground systems at lower frequencies to fill in the details of the discharges at lower levels.

The lower left panel of Fig. 6-3 shows LDAR data on a map of the East coast of Florida (partially shown). The data are then projected on an East-West vs. altitude panel (upper left) and a North-South vs. altitude panel (lower right, note that this panel is turned 90 degrees on its side). A histogram (upper right) displays the data in five one-minute increments.

FIGURE 6-3

Real-time LDAR display
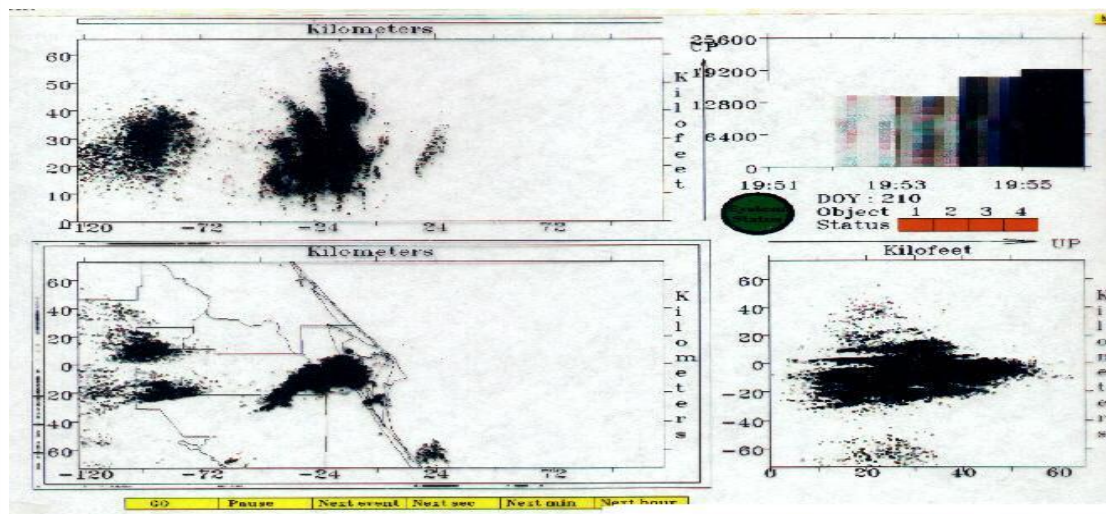
Meteo-06-03

6.7   Ground-based remote sensing

Vertical atmospheric sounding using passive remote sensing from satellites is described in detail in § 5.1. Meteorologists making detailed local forecasts or scientists investigating the planetary boundary have requirements for atmospheric sounding with better vertical resolution near the ground than cannot be provided by the satellite systems.

One method of providing this information is to use upward-looking passive remote sensing, with a radiometer mounted at the Earth's surface. These radiometers use a selection of channels in the oxygen band between 50 GHz and 58 GHz to produce a measurement of temperature structure. Channels between 21 GHz and 24 GHz are used to provide information on the variation of water vapour in the vertical, and a window observation in the region of 30 GHz is used for cloud identification. Measurement of water vapour also benefits from additional observations in the lower wings of the water vapour absorption band at 183 GHz.

Although the channels for ground based remote sensing of temperature and humidity are in a similar region to passive satellite remote sensing, they are in general using wider bands including bands shared with other services. In some frequency bands, in particular those covered by RR No. **5.340**, ground-based radiometers benefit from the same protection than satellite remote sensing but in other bands, ground-based radiometers would require relevant protection. The number of ground-based radiometers in operation is still relatively small, but larger numbers are expected to be deployed in a near future. A pragmatic method of sharing may have to be developed where radiometers are deliberately sited to avoid interference from the other services.

Passive remote sensing of other atmospheric constituents, e.g. ozone (in particular at 142 GHz) also benefits from a significant number of ground-based radiometry sites.

6.8   Unmanned Aircraft Systems

Unmanned Aircraft Systems (UAS) are becoming increasingly important for meteorological and Earth observations operations. UAS address observation requirements in areas where traditional systems cannot be deployed, where manned aircraft flights are not possible due to long flight durations and where hazardous conditions exist (e.g. hurricanes, cyclones). UAS operations (2008) for meteorological purposes often use unlicensed spectrum for command and control of the aircraft, though some systems do use licensed frequencies. UAS are used for applications that include routine release of dropsondes over ocean areas where radiosonde data has historically been missing, flights into hurricanes and cyclones for *in situ* data collection, aerial reconnaissance of areas impacted severe weather or drought conditions, and monitoring of arctic ice melt.

Use of UAS for meteorological operations improve the prediction hurricane landfall areas, extend lead times provided to the public and allow for increased understanding of climate. In addition to the command and control of the UAS, spectrum is needed for payload data transmission. This could be accommodated in suitable bands allocated for meteorological purposes (MetAids) or, depending on the data volume, in other frequency bands.

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Recommendation ITU-R F.699-7 – 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 F.1245-2 – Mathematical model of average and related radiation patterns for line-of-sight point-to-point fixed wireless system antennas for use in certain coordination studies and interference assessment in the frequency range from 1 GHz to about 70 GHz

Recommendation ITU-R M.1652-1 – Dynamic frequency selection in wireless access systems including radio local area networks for the purpose of protecting the radiodetermination service in the 5 GHz band

Recommendation ITU-R M.1849-1 – Technical and operational aspects of ground-based meteorological radars

Recommendation ITU-R RS.515 – Frequency bands and bandwidths used for satellite passive sensing

Recommendation ITU-R RS.577 – Frequency bands and required bandwidths used for spaceborne active sensors operating in the Earth exploration-satellite (active) and space research (active) services

Recommendation ITU-R RS.1166 – Performance and interference criteria for active spaceborne sensors

Recommendation ITU-R RS.2017 – Performance and interference criteria for satellite passive remote sensing

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Annex 1

Acronyms and abbreviations commonly used in meteorology

A

A/D	Analogue-to-digital
AAAS	American Association for the Advancement of Science
AARS	Automated Aircraft Reporting System
ABSN	Antarctic Basic Synoptic Network
ACARS	Aircraft Communications Addressing and Reporting System
ACCAD	Advisory Committee on Climate Applications and Data
ACMAD	African Centre of Meteorological Applications for Development
ADAS	Airborne Data Acquisition System
ADC	Analogue-to-Digital Converter
ADEOS	Advanced Earth Observation Satellite (Japan)
ADP	Automatic Data Processing
ADPE	Automatic Data Processing Equipment
AFC	Automatic Frequency Control
AFOS	Automatic Forecasting and Observing System
AGC	Automatic Gain Control
AGRHYMET	Regional Training Centre for Agrometeorology and Operational Hydrology and its Applications
AIRS	Advanced Infrared Sounder (NASA instrument)
ALC	Automatic Level Control
AM	Amplitude Modulation
AMDAR	Aircraft Meteorological Data Relay
AMI	American Meteorological Society
AMSR	Advanced Meteorological Temperature Sounder
ANSI	American National Standards Institute
AOPC	Atmospheric Observation Panel for Climate
AOS	Acquisition of Signal
APT	Automatic Picture Transmission
ARGOS	Data collection and location system on NOAA series satellites
ASCII	American Standard Code for Information Interchange
ASIC	Application Specific Integrated Circuit
ATMS	Advanced Technology Microwave Sounder (NPOESS/NASA)
ATOVS	Advanced TIROS Operational Vertical Sounder

ATSR	Along-Track Scanning Radiometer
AVCS	Advanced Video Camera System
AVHRR	Advanced Very High Resolution Radiometer
AWIPS	Advanced Weather Information Processing System

B

BCD	Binary Coded Decimal
BER	Bit Error Rate
BPS	bits per second
BPSK	Binary Phase Shift Keying
BR	ITU Radiocommunication Bureau
BW	Bandwidth

C

C/N_0	Carrier-to-noise density ratio
C&DH	Command and Data Handling
CaeM	Commission for Aeronautical Meteorology
CAgM	Commission for Agricultural Meteorology
CAS	Commission for Atmospheric Sciences
CBS	Commission for Basic Systems
CCD	Charge Coupled Device
CCIR	International Radio Consultative Committee (see ITU-R)
CCl	Commission for Climatology
CCRS	Canada Centre for Remote Sensing
CCSDS	Consultative Committee for Space Data Systems
CDA	Command and Data Acquisition
CDAS	Command and Data Acquisition Station
CEOS	Commission on Earth Observation Satellites
CERES	Cloud and Earth's Radiative Energy System
CGMS	Co-ordination Group for Meteorological Satellites
CHy	Commission for Hydrology (WMO)
CIESIN	Consortium for International Earth Science Information Networks
CIMO	Commission for Instruments and Methods of Observation
CIMSS	Cooperative Institute for Meteorological Satellite Studies
CLICOM	Climate Computing
CLINO	Climatological Normals
CLIPS	Climate Information and Prediction Services

C (*cont.*)

CLIVAR	Climate Variability and Predictability
CMA	China Meteorological Administration
CMD	Command
CMIS	Conical-scanning Microwave Imager/Sounder (NPOESS instrument)
CMM	Commission for Marine Meteorology
CNES	Centre National d'Etudes Spatiales
CNIE	Comisión Nacional de Investigaciones Espaciales
COADS	Comprehensive Ocean-Atmosphere Data Set
CONUS	Continental United States
COP	Conference of the Parties
COPUOS	Committee on the Peaceful Uses of Outer Space
CORSSAC	Civil Operational Remote Sensing Satellite Advisory Committee
COSPAS	A Russian satellite-borne search and rescue system. See SARSAT
CPCSA	Climate Program Coordination and Support Activities
CPR	Cloud Physics Radiometer, or Cardio-pulmonary Resuscitation
CPU	Central Processing Unit
CRC	Cyclic Redundancy Check/Cyclic Redundancy Code
CrIS	Cross-track Infrared Sounder (NPOESS instrument)
CrMIS	Cross-track Microwave Imager-Sounder (NPOESS instrument)
CRT	Cathode Ray Tube
CSA	Canadian Space Agency
CS&C	Communications Switching and control (CDA portion of GMACS System)
CSIRO	Commonwealth Scientific and Industrial Research Organization
CSIS	Centralised Storm Information System
CSM	Climate System Monitoring
CSMA/CD	Carrier Sensing Multiple Access with Collision Detection
CSTR	Council for Scientific and Technical Research
CTCS	CDA Telemetry and Command System (CDA portion of GIMTACS System)
CW	Continuous Wave
CZCS	Coastal Zone Colour Scanner

D

D/A	Digital-to-analogue
DAAC	Distributed Active Archive Center
DADS	Data Archive and Distribution System
DAPS	DCS Automated Processing System
DAS	Data Acquisition System
DAS	Data Base Administration System

DAS	Direct Access System
dB	Decibel
DB	Direct Broadcast
DBMS	Database Management System
DCPLS	Data Collection Platform Location System
DCP	Data Collection Platform
DCPI	Data Collection Platform Interrogation
DCPR	Data Collection Platform Reception
DCR	Differential Correlation Radiometer
DCS	Data Collection System
DEMUX	De-Multiplexer
DIFAX	Digital Facsimile
DIR	Daytime Infrared
DLI	Down-Link Interface (DM/PM)
DLM	Down-Link Monitor
DLR	German Space Agency (Deutsche Zentrum fur Lüft- und Raumfahrt)
DMSP	Defense Meteorological Satellite Program
DN	Descending Node
DOMSAT	Domestic (Communications) Satellite
DPT	Digital Picture Terminal
DR	Direct Readout
DRGS	Direct Readout Ground Stations
DS	Dwell Sounding or Sounding (GOES-4/7 VAS operating node)
DSARS	DAMUS Satellite Archive and Retrieval System
DSB	Direct Sounder Beacon
DSB	Direct Sounder Broadcasts
DSN	Deep Space Network
DUS	Data Utilisation System

E

EBR	Electron Beam Recorder
EC/AGE	Executive Council Advisory Group on the Exchange of Meteorological and Electronics Calibration
ECMWF	European Centre for Medium-range Weather Forecasts
EDC	EROS Data Center
EDIMS	Environmental Data & Information Management Systems
EES	Earth Exploration Satellite
EESS	Earth Exploration-Satellite Service
EIRP	Equivalent Isotropically Radiated Power
EIRPSD	Equivalent Isotropically Radiated Power Spectral Density
ELT	Emergency Locator Transmitter
ELV	Expendable Launch Vehicle
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
ENSO	*El Niño*/Southern Oscillation
ENVISAT	Environmental Satellite
EOS	Earth Observation Satellites
EPIRB	Emergency Position-Indicating Radio Beacon

E (*cont.*)

EPOCS	Equatorial Pacific Ocean Climate Studies
EPS	Energetic Particle Sensor
ERB	Earth Radiation Budget
ERBE	Earth Radiation Budget Experiment
ERL	Environmental Research Laboratory
EROS	Earth Resources Observing Satellite
ERS	ESA Remote Sensing Satellite
ESA	European Space Agency
ESD	Electrostatic Discharge
ESMR	Electronically Scanning Microwave Radiometer
ETA	Estimated Time of Arrival
ETM	Engineering Test Model
ETM	Enhanced Thematic Mapper
ETS	Engineering Test Satellite
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
EUV	Extreme Ultraviolet

F

FAX	Facsimile
FC	False Colour
FCC	False Colour Composite
FCC	Federal Communications Commission
FDM	Frequency Division Multiplexing
FFT	Fast Fourier Transform
FIFO	First-In-First-Out
FM	Frequency Modulation
FOV	Field of view
fps	Frames Per Second
FSK	Frequency Shift Keying
FSS	Fixed-Satellite Service
FSS	Flight Scheduling Software System

G

GAC	Global Area Coverage
GAME	GEWEX Asian Monsoon Experiment
GARP	Global Atmospheric Research Program
GARS	GOES Archive and Retrieval System
GAW	Global Atmosphere Watch
GCIP	GEWEX Continental-scale International Project
GCM	General Circulation Model
GCOS	Global Climate Observing System
GDTA	Groupement pour le Développement de la Télédétection Aérospatiale
GEO	Geostationary Earth Orbit
GEWEX	Global Energy and Water Cycle Experiment
GHz	Gigahertz
GIMGSP	GOES I-M Ground System Project
GIMTACS	GOES I/M Telemetry and Command System
GIS	Geographical Information Systems

GMACS	GOES Monitoring and Control system (current GIMTACS)
GMDSS	Global Maritime Distress and Safety System
GMS	Geostationary Meteorological Satellite
GMT	Greenwich Mean Time
GNSS	Global Navigation Satellites Systems
GOES	Geostationary Operational Environmental Satellite
GOMS	Geostationary Operational Meteorological Satellite
GOOS	Global Ocean Observing System
GOS	Global Observing System
GOSSP	Global Observing Systems Space Panel
GPCP	Global Precipitation Climatology Project
GPS	Global Positioning System
GPSOS	GPS Occultation Sensor
GRC	Glenn Research Center formerly the Lewis Research Center (LeRC)
GRS	Ground Receiving Station
GRT	GOES Real-time (database)
GSFC	Goddard Space Flight Center
GSN	GCOS Surface Network
GSTDN	Ground Spaceflight Tracking and Data Network
G/T	Antenna Gain to System Noise Temperature Ratio (dB/K)
GTOS	Global Terrestrial Observing System
GTS	Global Telecommunications System
GUAN	GCOS Upper-air Network
GVAR	GOES VARiable
GWC	Global Weather Center

H

H1/3	Significant wave height
HEPAD	High Energy Proton and Alpha Detector
HiRID	High Resolution Imager Data
HIRS	High-resolution Infrared Sounder (TIROS instrument)
HOMS	Hydrological Operational Multipurpose System
HRD	Hurricane Research Day
HRD (10)	Hurricane Research Day – GOES-East scans every 10 minutes at selected times.
HRIS	High Resolution Infrared Sounder, or High Resolution Interferometric Sounder
HRPT	High Resolution Picture Transmission
HRSD (S)	Hurricane Rapid Scan Day (Stereo) GOES-East and West scan every 7 1/2
Hz	Hertz formerly cycles per second

I

I/O	Input/Output
I/S	Imager and Sounder
IAHS	International Association of Hydrological Sciences
IAMAS	International Association of Meteorology and Atmospheric Sciences
IASI	Infrared Atmospheric Sounding Interferometer
ICES	International Council for the Exploration of the Sea
ICSAR	International Committee for Search and Rescue
ICSU	International Council of Scientific Unions
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate Frequency
IFOV	Instantaneous Field of View
IFRB	International Frequency Registration Board (see BR)
IGBP	International Geosphere-Biosphere Programme
IGF	Image Generation Facility
IGFOV	Instantaneous Geometric Field of View
IGOSS	Integrated Global Ocean Services System
IHP	International Hydrological Programme
INDOEX	Indian Ocean Experiment
INPE	Instituto de Pesquisas Espaciales
INR	Image Navigation and Registration
INR	Interference to Noise Ratio
INSAT	Indian Satellite
IOC	Intergovernmental Oceanographic Commission
IODE	International Oceanographic Data and Information Exchange
IPCC	Intergovernmental Panel on Climate Change
lPD	IF Presence Detector (CDA)
IR	Infrared
IRIG	Inter-Range Instrumentation Group
IRIS	Infrared Interferometer Spectrometer
IRS	Indian Remote Sensing Satellite
IRU	Inertial Reference Unit
ISETAP	Intergovernmental Science Engineering & Technology Advisory Panel
ISO	International Organization for Standardization
ITOS	Improved TIROS Operational System
ITPR	Inferred Temperature Profile Radiometer
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector (former CCIR and IFRB)

J

JDIMP	Joint GCOS/GOOS/GTOS Data Management and Information Panel
JERS	Japanese Earth Resources Satellite
JIC	Joint Ice Center
JMA	Japan Meteorological Agency
JPL	Jet Propulsion Laboratory
JSC	Joint Scientific Committee Johnson Space Center
JSTC	Joint Scientific and Technical Committee

K

K	Kelvin
kbit	kilobit(s)
kB	kilobyte(s)
kbit/s	kilobits per second
keV	Thousand Electron Volts
kHz	kilohertz
KSC	Kennedy Space Center
KSPS	kilo samples per second

L

LANDSAT	U.S. earth remote sensing satellite
LANDSAT-TM	Landsat Thematic Mapper instrument
LaRC	Langley Research Center
LAT/LON	Latitude/Longitude
LE	Landmark Extraction
LEO	Low Earth Orbit
LEOP	Launch and Early Orbit Phase
LeRC	see GRC
LGSOWG	LANDSAT Ground Station Operations Working Group
LHCP	Left-Hand Circular Polarisation
LIDAR	Light Detection and Ranging
LMT	Local Mean Time
LOS	Loss of Signal
LPA	Low Power Amplifier
lpi	lines per inch
lpm	lines per minute
LRIT	Low Rate Information Transmission
LRPT	Low Resolution Picture Transmission
LUT	Look-up Table, or Local User Terminal
LW	Long Wave
LWIR	Long Wave Infra-Red

M

mb	Millibars
Mbit/s	Megabits per second
MB/s	Megabytes per second
MCC	Mission Control Center
MCDW	Monthly Climatic Data for the World
MCS	Moisture Channel Support
MDHS	Meteorological Data Handling System
MDUS	Medium-scale Data Utilisation Stations
MEO	Medium Earth Orbit

M (*cont.*)

MEPED	Medium Energy Proton and Electron Detector
MetAids	Meteorological Aids
METEOSAT	European Geostationary Meteorological Satellite
METOP	European Polar-orbiting Meteorological Satellite
MetSat	Meteorological Satellite
MeV	Million Electron Volts
MeV/n	Million Electron Volts Per Nucleon
MHS	Microwave Humidity Sounder
MHz	Megahertz
MLS	Microwave Limb Sounder
MODEM	Modulator/Demodulator
MODIS	Moderate Resolution Imaging Spectroradiometer (NASA instrument)
MOPITT	Measurement of Pollution in the Troposphere (NASA)
MOS	Marine Observation Satellite (Japan)
MPERSS	Marine Pollution Emergency Response Support System
mr	Milliradians
MSFC	Marshall Space Flight Center
MSI	Multi-spectral Imaging
MSS	Mobile-Satellite Service
MSS	Multi-spectral Scanner
MSU	Microwave Sounding Unit
MTBF	Mean Time Between Failures
MTF	Modulation Transfer Function
MUX	Multiplexer
MW	Momentum Wheel Medium wave Microwave Megawatt

N

N/S	North/South
NASA	National Aeronautics and Space Administration
NASCOM	NASA Communications Network
NASDA	National Space Development Agency
NCDC	National Climatic Data Center
NE-delta-N	Noise Equivalent Change in Radiance
NE-delta-T	Noise Equivalent Change in Temperature
NERC	National Environmental Research Council
NESDIS	National Environmental Satellite Data and Information Service
NF	Noise Figure
NHC	National Hurricane Center

N (*cont.*)

NHS	National Hydrological Service
NIR	Night Infrared, or Near Infrared
NMC	National Meteorological Center
NMS	National Meteorological or Hydrometeorological Service
NNODS	NOAA/NOSS Ocean Data System

NOAA	National Oceanic and Atmospheric Administration
NOAA	Polar METSAT
NOS	National Ocean Survey
NPOESS	National Polar-Orbiting Operational Environmental Satellite System
NRCT	National Research Council of Thailand
NROSS	Navy Remote Ocean Sensing System
NRSA	National Remote Sensing Agency
NRZ	Non-Return to Zero
NRZ-L	Non-Return to Zero Level
NSSFC	National Severe Storms Forecast Center
NSSL	National Severe Storms Laboratory
nT	Nano Tesla
NWP	Numerical Weather Prediction
NWS	National Weather Service

O

O&M	Operations and Maintenance
OAD	Orbit and Attitude Determination
OAR	Office of Oceanic and Atmospheric Research
OCTS	Ocean Colour Temperature Sensor
OHP	Operational Hydrology Programme
OMI	Ozone Measuring Instrument
OMPS	Ozone Mapping and Profiler Suite (NPOESS)
OOPC	Ocean Observations Panel for Climate
OQPSK	Offset QPSK

P

P/SEC	Pulses per second
P-P	Peak to Peak
PA	Power Amplifier
PAM	Pulse Amplitude Modulation
PCM	Pulse Code Modulation
PDL	Processor Data Load
PDR	Processed Data Relay (GVAR RF link)
PE	Primitive Equation
PEP	Peak Envelope Power
PEP	Polynomial Error Protection (NASA)
PFD	Power Flux-Density
Pixels	Picture Elements
PKM	Perigee Kick Motor
PLL	Phase Locked Loop
PM	Phase Modulation
PN	Pseudonoise
POES	Polar-orbiting Operational Environmental Satellite
PPM	Parts per million
PPS	Pulses per second
PR	Precipitation Radar
PRF	Pulse Repetition Frequency
PROFS	Program for Regional Observing and Forecasting Service
PROMET	Working Group on the Provision of Meteorological Information

PSK	Phase Shift Keying

P (*cont.*)

PWM	Pulse-width Modulation

Q

QC	Quality Control
QPSK	Quadrature PSK

R

R	Rayleigh
RA	Radar Altimeter
R/Y	Roll/Yaw
R&D	Research and Development
RBSN	Regional Basic Synoptic Network
RCS	Reaction Control System
RF	Radio Frequency
RFI	Radio Frequency Interference
RGB	Red/Green/Blue
RH	Relative Humidity
RHCP	Right-Hand Circular Polarisation
RMDCN	Regional Meteorological Data Communication Network
RMS	Root Mean Square
RPM	Revolutions Per Minute
RSS	Root Sum of the Squares
RSU	Remote Sensing Unit
RT	Real Time
RW	Reaction Wheel
RWA	Reaction Wheel Assembly

S

S/C	Spacecraft
S/N	Signal-to-noise ratio
S/N$_0$	Signal-to-noise density ratio
S-VAS	Stretched Visible Infrared Spin Scan Radiometer Atmospheric Sounder
S-VISSR	Stretched Visible Infrared Spin Scan Radiometer
SAD	Sounder/Auxiliary Data
SAGE	Stratospheric Aerosol and Gas Experiment
SAR	Synthetic Aperture Radar, or Search and Rescue
SARSAT	Search And Rescue Satellite-Aided Tracking; see COSPAS
SATCOM	Satellite Communications
SBUV	Solar Backscatter Ultraviolet
SC/N$_0$	Subcarrier-to-noise density ratio
SC/OMS	Subcommittee on Operational Meteorological Satellites
SC/OES	Subcommittee on Operational Environmental Satellites
SCHOTI	Standing Conference of Heads of Training Institutions of National Meteorological Services
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Cartography
SCO	Subcarrier Oscillator

SCSMEX	South China Sea Monsoon Experiment
SDUS	Small-scale Data Utilisation Station
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SEC	Second
SEM	Space Environment Monitor
SEU	Single Event Upset
SGLS	Space Ground Link System
SIGWX	Significant Weather
SIR	Shuttle Imaging Radar
SIRS	Satellite Infrared Spectrometer
SIT	CEOS Strategic Implementation Team
SLAR	Side-looking Airborne Radar
SN	Space Network
SNR	Signal-to-Noise Ratio
SOCC	Spacecraft Operations Control Center
SOES	Subcommittee on Operational Environmental Satellites
SOLAS	International Convention for the Safety of Life at Sea
SPM	Solar Proton Monitor
SPOT	Satellite Probatoire d'Observation de la Terre
SQPSK	Staggered QPSK
SPREP	South Pacific Regional Environment Programme
SR	Scanning Radiometer
sr	Steradian
SR-IR	Scanning Radiometer-Infrared Channel
SR-VIS	Scanning Radiometer-Visible Channel
SSA	WWW System Support Activities
SSM/I	Special Sensor Microwave/Imager
SST	Sea Surface Temperature
SSU	Stratospheric Sounding Unit
STA	Science and Technology Agency
STC	Scientific and Technical Committee
Ster	Steradian
STS	Space Transportation System
SW	Short wave
SW	Switch
SWIR	Short Wave Infrared
SXI	Solar X-ray Imager
SXT	Solar X-ray Telescope (Solar-A mission)

T

T/P	Topex/Poseidon
T/V	Thermal Vacuum

T (*cont.*)

T&C	Telemetry and Command
TBUS	A 4-1etter designator for Ephemeris data message
TDM	Time Division Multiplexing
TDRS	Tracking and Data Relay Satellite
TDRSS	Tracking and Data Relay Satellite System
TED	Total Energy Detector, or Turtle Excluder Device
TEMS	Terrestrial Ecosystem Monitoring System
TES	Tropospheric Emission Spectrometer
TIP	TIROS Information Processor
TIR	Thermal Infrared
TIROS	Television Infra-Red Observational Satellite
TLM	Telemetry
TM	Thematic Mapper
TMI	TRMM Microwave Imager
TMR	Topex Microwave Radiometer
TO	Transfer Orbit
TOGA	Tropical Ocean and Global Atmosphere
TOPC	Terrestrial Observation Panel for Climate
TOMS	Total Ozone Mapping Spectrometer
TOS	TIROS Operational System
TOVS	TIROS Operational Vertical Sounder
TRMM	Tropical Rainfall Measurement Mission
TRUCE	Tropical Urban Climate Experiment
TT&C	Tracking Telemetry
TV	Thermal Vacuum, or Television
TVM	Transparent VAS Mode

U

UHF	Ultra-High Frequency
UNEP	United Nations Environment Programme
μrad	Microradian
μs	Microsecond
UTC	Universal Time Coordinated
UV	Ultraviolet

V

VAS	VISSR Atmospheric Sounder
VCP	Voluntary Cooperation Programme
VDB	VISSR Data Base
VDUC	VAS Data Utilisation Center
VHF	Very High Frequency
VIIRS	Visible Infrared Imager/Radiometer Suite (NPOESS instrument)
VIP	VAS Image Processor (with P/DU current SPS)
VIRGS	VISSR Image Registration and Gridding System
VISSR	Visible & Infrared Spin Scan Radiometer

VOS	Voluntary Observing Ship
VREC	Very High Resolution Radiometer Data Recorder
VSWR	Voltage Standing Wave Ratio
VTPR	Vertical Temperature Profile Radiometer

W

WAFC	World Area Forecast Centre
WCASP	World Climate Applications and Services Programme
WCDA	Wallops Command and Data Acquisition (Station)
WCDMP	World Climate Data and Monitoring Programme
WCFP	World Climate Data Programme
WCP	World Climate Programme
WCRP	World Climate Research Programme
WDC	World Data Centre
WEFAX	Weather Facsimile
WHYCOS	World Hydrological Cycle Observing System
WMO	World Meteorological Organization
WRC	World Radiocommunication Conference
WSFO	Weather Service Forecast office
WSFO-Tap	WSFO ground communications link relaying GOES data
WWRP	World Weather Research Programme
WWW	World Weather Watch
WX	Weather

X

XBT	Expendable Bathythermograph
XRI	X-Ray Imager
XRS	(Solar) X-Ray Sensor

Y

yr	Year

Z

Z	Common abbreviation for Greenwich Meridian Time or Universal Time