World
Meteorological
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International
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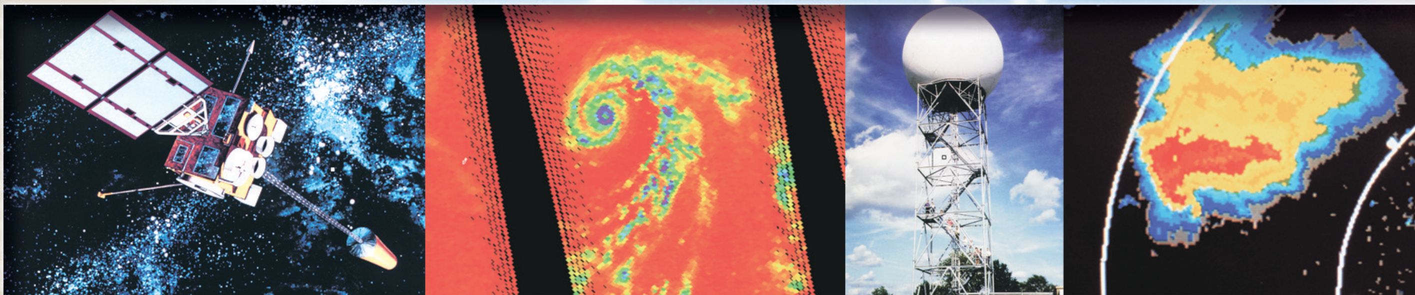
Union

# HANDBOOK



# Use of Radio Spectrum for Meteorology

Edition 2002

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# PREFACE

The Handbook on Use of Radio Spectrum for Meteorology has been developed by experts of Working Party 7C of ITU-R Radiocommunication Study Group 7 (Science Services) under the chairmanship of Mr. E. Marelli (ESA), Chairman, Radiocommunication Working Party 7C.

The Handbook in its six Chapters provides comprehensive technical information on the use of radio frequencies by meteorological systems, including meteorological satellites, radiosondes, weather radars, wind profiler radars, spaceborne remote sensing, etc.

It is intended for all users, practitioners, technicians, developers and other interested parties and individuals of the meteorological and radiocommunication communities, including governmental institutions and the industry.

Robert W. Jones
Director, Radiocommunication Bureau

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# FOREWORD

The Radiocommunication Study Group 7 (SG 7) for the Science Services was created through a structure reorganization in 1990 at the Düsseldorf CCIR Plenary Assembly. Many of the activities in SG 7 are associated with advancing the state of the art in the use of the radio spectrum to achieve scientific objectives.

SG 7 currently comprises a number of Radiocommunication Working Parties (WP) that address technical issues related to specific disciplines under the umbrella of science services. Meteorology falls within the remit of Working Party 7C, and includes studies of the implementation and operation of meteorological sensors, both passive and active, from both ground-based and space-based platforms. Meteorology 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. Activities that result in constant media attention include:

– weather satellites track the progress of hurricanes and typhoons;

– weather radars track the progress of tornadoes, thunderstorms, and the effluent from volcanoes and major forest fires;

– radio-based meteorological aid systems collect and process weather data, without which the current and planned accuracy of weather predictions would be seriously compromised; and

– broadcast sound and television systems warn the public of dangerous weather events, and aircraft pilots of storms and turbulence.

While the development of Recommendations continues to be the principal focus of the Study Group activities, it has become clear that the experts who work on these matters in the Study Group have much basic information to offer to their scientific and lay colleagues who depend on meteorological data for improving the accuracy of weather and climate prediction, and data acquisition methods.

Thus it was decided to prepare and publish this Handbook, in collaboration with the Steering Group on Radio Frequency Coordination 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 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. For example, if the frequency bands currently allocated for meteorological purposes were to be allocated to other radio services that are incompatible with meteorological radio systems, then these bands could be rendered unusable for weather prediction systems, thus making weather forecasting impossible.

As Chairman of SG 7, it is my honor and 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.

The Handbook could not have been completed without the contributions from many administrations participating in SG 7. However, 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) and Mr. Jean-Michel Rainer (WMO), and to the Chairman of WP 7C, Mr. Edoardo Marelli (ESA) for his leadership of this project. Our special gratitude is also due to Mr. A. Nalbandian of the Radiocommunication Bureau who has played an important role in the publication of the Handbook.

R. M. Taylor
Chairman, Radiocommunication
Study Group 7

## STUDIES ON SHARING SPECTRUM

Conflict is inevitable, and has resulted in a profusion of studies within the International Telecommunication Union (ITU) and its Radiocommunication Sector (ITU-R) seeking to determine how spectrum can be made available for new uses, many of which are by non-meteorological users. These studies have focused largely on spectrum requirements and questions of technical compatibility – whether, and under what conditions, emerging technologies could share spectrum with existing systems. These studies have discovered instances where co-channel sharing is not possible and making additional spectrum available to emerging technologies would involve displacement of existing users, inevitably raising certain questions.

– Are the projected spectrum requirements for the new technologies realistic?
– Should current users be forced to vacate all or significant portions of a band?
– Can current meteorological users afford to change to a new band? Here, one must remember that not all existing systems are operated by wealthy nations or by profit-making entities.
– If necessary, can financial assistance be provided by the potentially profitable new technologies?
– If displaced, how much time must reasonably be allowed to permit current band occupants to relocate?

In an attempt to place these studies in perspective, Radiocommunication Working Party 7C "Earth Exploration Satellite Systems and Meteorological Systems" of Radiocommunication Study Group 7 and the Steering Group on Radio Frequency Coordination of the World Meteorological Organization (WMO) have prepared this Handbook.

This Handbook 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 wireless telecommunications industry. Meteorological systems are defined and an overview and discussion of each system's technical characteristics is provided. 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
3. Meteorological aids service systems
4. Meteorological radars, including:
4.1 Rotating weather radars
4.2 Wind profiler radars
5. Earth exploration-satellite service (EESS) systems for meteorological activities, including:
5.1 Passive microwave radiometry sensing
5.2 Active sensing systems

6. Other radiocommunication systems for meteorological activities, including:

6.1 Broadcasting and dissemination systems

6.2 Hydrological remote systems

6.3 Fixed remote systems

6.4 Radionavigation systems

6.5 Lightning detection and location systems

6.6 Ground based passive remote sensing systems.

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.

This Handbook focuses on systems that collect and transmit meteorologically observed data and the relation of these systems to the use of RF spectrum.

# CHAPTER 1

## GENERAL STRUCTURE OF METEOROLOGICAL SYSTEMS

## 1.1 Meteorological systems of the World Weather Watch

The World Weather Watch (WWW) is the basic programme of the World Meteorological Organization (WMO) and is implemented and operated by the 185 WMO Member States. The WWW is composed of three integrated core system components (see Fig. 1-1):

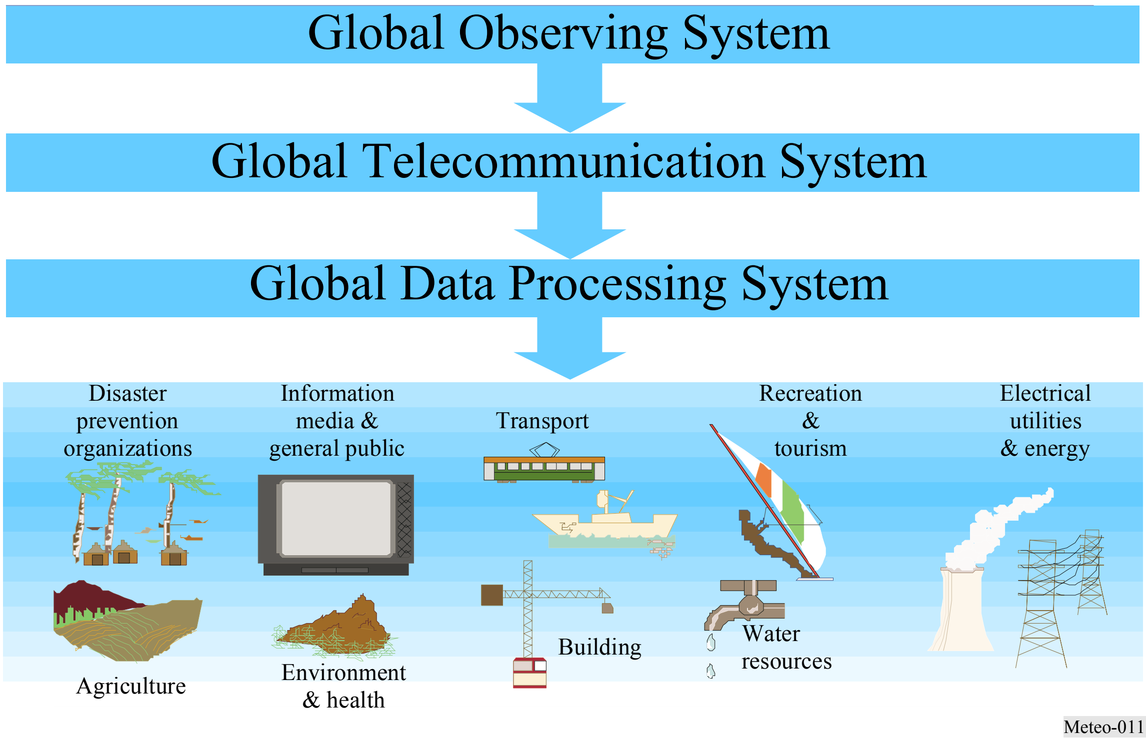
– The **Global Observing System (GOS)** provides high-quality, standardized observations of the atmosphere and ocean surface from all parts of the globe and from outer space.

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

– 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.

FIGURE 1-1

**World Weather Watch systems**




### 1.1.1 Global Observing System

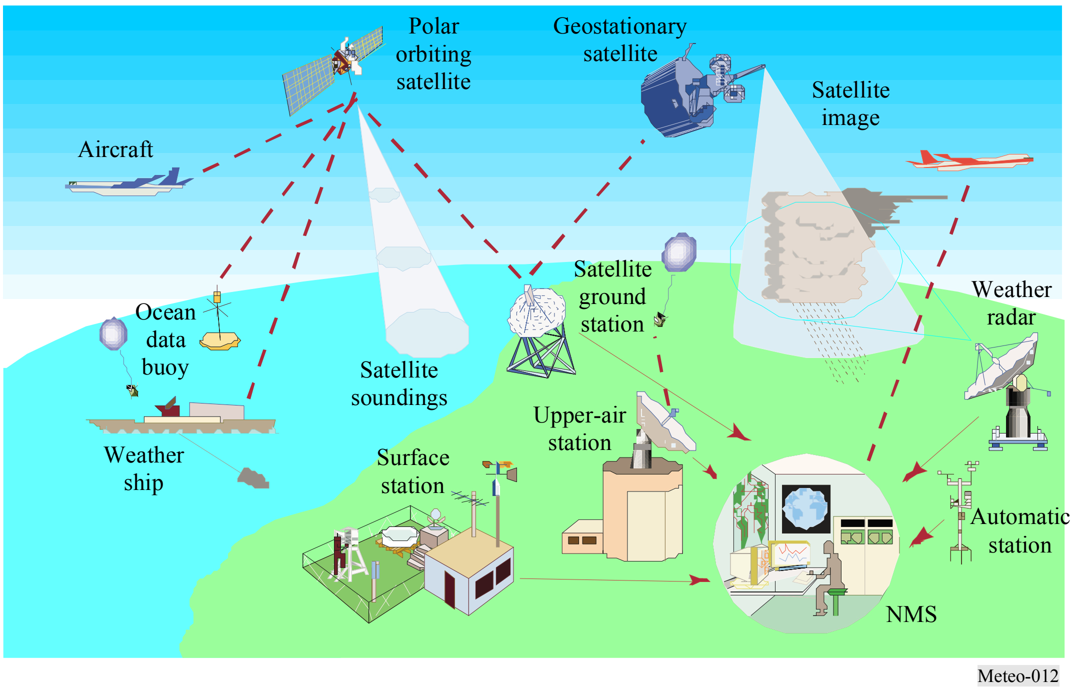
The Global Observing System (GOS) is comprised of observing stations located on land, at sea, on aircraft, and on meteorological satellites as shown in Fig. 1-2. The GOS is the primary source of technical information on the world's atmosphere. GOS is a composite system of complex methods, techniques 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. 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, and extra-tropical and tropical cyclones. GOS provides observational data for agrometeorology, aeronautical meteorology and climatology, including the study of climate and global change. A wide range of economic activities such as farming, transportation, construction, public weather services, and tourism benefit enormously from weather forecasts that extend from a few days, to weeks, or even seasons. Data from GOS are also used in support of environmental programmes everywhere.

#### 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 is also used in the Global Climate Observing System (GCOS).

FIGURE 1-2

**GOS**




#### 1.1.1.2 Upper-air observing

From a network of roughly 900 upper-air stations around the world, 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 15 ships, which mainly ply the North Atlantic, fitted with automated shipboard upper-air sounding facilities.

### 1.1.1.3 Radar observations

Doppler 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. Doppler radars are used extensively as part of national, and increasingly of regional networks, mainly for short-range forecasting of severe weather phenomena. Particularly useful is the Doppler radar capability of making wind measurements and estimates of rainfall amounts. 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 6 700 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 drifting buoy programme comprises about 700 drifting buoys providing 3 500 sea surface temperature and surface air pressure reports per day.

### 1.1.1.5 Observations from aircraft

Over 3 000 aircraft provide reports of pressure, winds, and temperature during flight. The Aircraft Meteorological Data Relay (AMDAR) system makes high-quality observations of winds and temperatures at cruising level, as well as at selected levels in ascent and descent. The amount of data from aircraft has increased ten-fold in recent years to an estimated 50 000 reports per day. 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 observation satellite network includes near-polar-orbiting satellites and geostationary environmental observation satellites (see Fig. 1-3). Polar orbiting and geostationary satellites are normally equipped with visible and infrared imagers and microwave sounders, from which one can derive many meteorological parameters. Several of the polar-orbiting satellites are equipped with sounding instruments that can provide vertical profiles of temperature and humidity in cloud-free areas. 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 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.

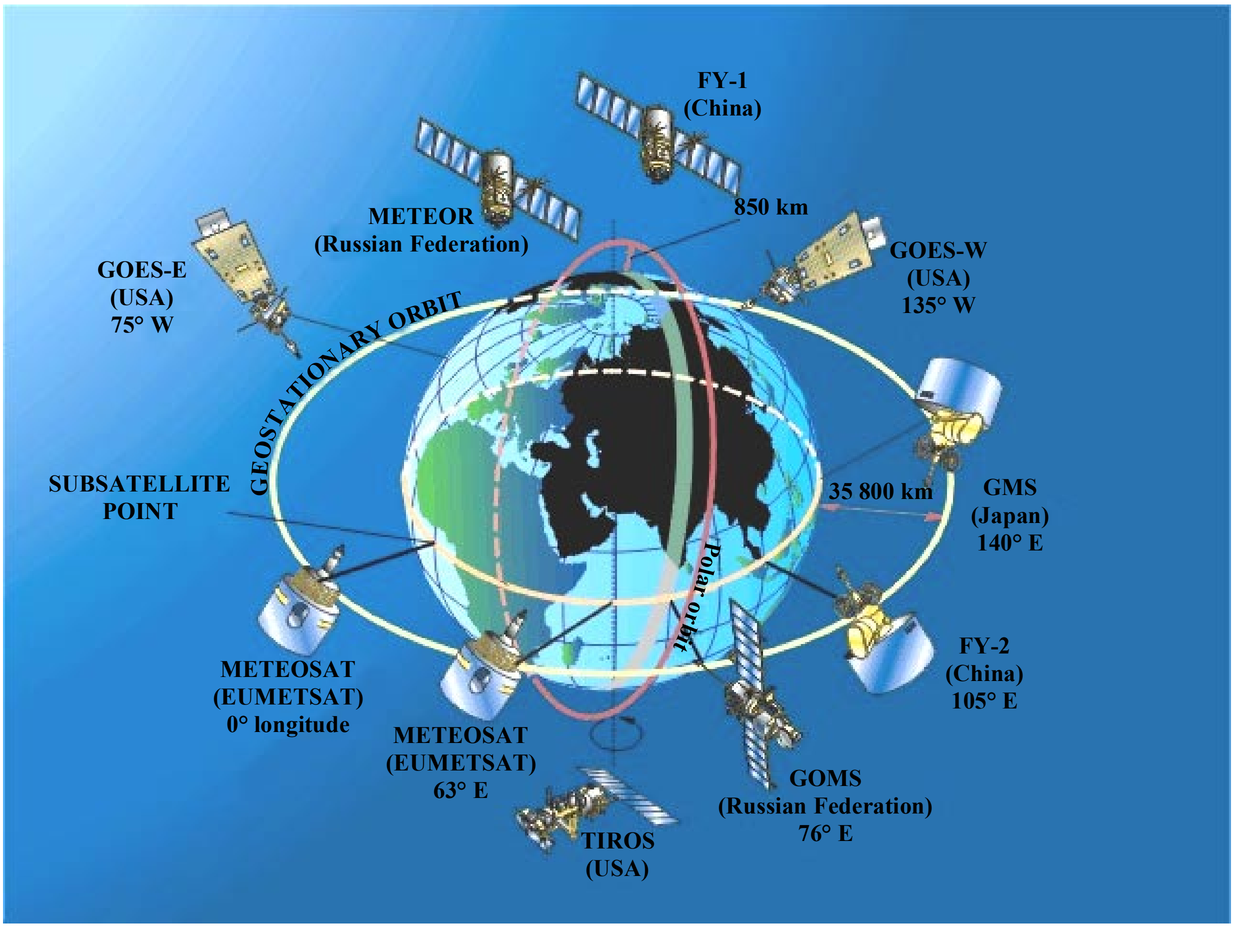
### 1.1.1.7 Future plans of GOS

The WWW GOS will continue to be a cost-effective system of operationally reliable surface and space-based (satellite) observing platforms. Future development will increase the spatial and time resolution of the observations. It is expected that, within the surface-based system, technologies such as wind profilers, Doppler and HF radars, and lightning detection networks will be deployed on a wider scale. Increasing use will be made of the rapidly growing fleet of aircraft with automated observing and reporting systems to supply data at cruising levels and during ascent and descent. Mobile sea stations will continue to be the main source of surface synoptic observations over the oceans.

The number of ships equipped with automated upper-air sounding facilities will increase and the development of more cost-effective systems will be accelerated. Drifting buoys deployed outside the main shipping routes will continue to supply surface atmospheric and oceanographic parameters from the data-void ocean areas. Through increased use of satellite automatic observing and transmission equipment, the quality and quantity of space-based data will increase. It is also expected that the operational space-based system will include a new generation of polar-orbiters and geostationary satellites with improved sensing systems. The role of satellites will increase through greater use of soundings and pseudo-soundings from geostationary satellites, and through increased numbers of channels and enhanced precision on sounders from polar orbiting satellites.

FIGURE 1-3

**Constellation of meteorological satellites**

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## 1.2 Other meteorological systems of 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 22 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 meteorological systems provide solar radiation observations, lightning detection, and tide-gauge measurements.

### 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. 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, which is based on a global network of reference stations, and which transmit hydrological and meteorological data in near real-time.

# CHAPTER 2

# METEOROLOGICAL SATELLITE SERVICE

## 2.1 Definition of the meteorological satellite service 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". The EESS allows radio-communication operation between earth stations and one or more space station with links to provide:

– Information relating to the characteristics of the Earth and its natural phenomena obtained from active or passive sensors on earth satellites.

– Information collected from airborne or earth-based platforms.

– Information distributed to earth stations.

This Chapter related to MetSat service applications includes the following radiocommunication transmissions (some of these systems are also known as Direct Readout Services):

– transmissions of observation data to main reception stations;

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

– direct broadcast transmissions to meteorological user stations.

ITU-R maintains a number of ITU-R Recommendations relating to the MetSat service. Other study groups also deal with issues of compatibility between the MetSat service and services with which they are involved. Given the extent of ongoing activity aimed at sharing meteorological spectrum with other services and other users, ITU-R Recommendations are constantly being revised and replaced while new ones are frequently added. For current information, the reader is referred to the ITU List of Publications.

The RF bands currently allocated to the MetSat service include the following:

| **Band (MHz)** | **Allocation** |
|---|---|
| **Space-to-Earth direction** | |
| 137-138 | Primary allocation |
| 400.15-401 | Primary allocation |
| 460-470 | Secondary allocation |
| 1 670-1 710 | Primary allocation |
| 7 450-7 550 | Primary allocation, geostationary satellites only |
| 7 750-7 850 | Primary allocation, non-geostationary satellites only |
| **Earth-to-space direction** | |
| 401-403 | Primary allocation |
| 8 175-8 215 | Primary allocation |

The MetSat service is a sub-class of the Earth exploration-satellite service, and therefore future MetSat applications could also use Earth exploration-satellite service allocations (as an example: 25.5-27 GHz). In addition, MetSats commonly collect data via passive sensing using frequencies allocated to that purpose. MetSats collect a variety of data by internal sensors providing photographic images taken at several wavelengths (see Chapter 5 on passive and active sensing).

Meteorological and Earth exploration satellites carry systems such as ARGOS that relay data sent to these systems by data collection platforms (DCPs) which may be on the ground, on aircraft, or on ships. DCPs typically transmit in the band 401-403 MHz to relay data collected on such parameters as surface temperature, wind velocity, rainfall rate, stream height, trace 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.

The raw data are commonly received on the ground by the operating agency, processed, and distributed to various weather services, to official archives, and to commercial users. Raw data includes photographs of the Earth taken at several wavelengths so as to provide a variety of useful information. Processed data are commonly sent back to the satellite to be retransmitted as part of a direct broadcast to user stations via weather facsimile (WEFAX) and high rate digital signals higher in the band.

## 2.2 MetSat service systems using GSO satellites

### 2.2.1 Raw image sensor data transmissions

Data obtained by the sensors on board 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. There are only a few stations of this type around the world, normally one or two per satellite system. They are equipped with antennas of approximately 10-18 m diameter and typically operate with a minimum elevation angle of 3°. The figure of merit of such stations is of the order of 23 dB/K. Typical bandwidths of the transmissions are between 2 MHz and 20 MHz depending on the sensor characteristics and modulation methods employed.

### 2.2.2 Data dissemination

#### 2.2.2.1 High resolution image dissemination

The high resolution image (HRI) dissemination service operates on METEOSAT spacecraft. The digital signal is broadcast at a data rate of 166.7 kbit/s using PCM/PM/SPL modulation. The HRI format is specific to METEOSAT, and the coverage zone is identical to the METEOSAT telecommunications area (i.e. GSO positioned at 0°). There are approximately 500 HRI primary data user stations registered with EUMETSAT. Data transmissions contain high-resolution images including calibration and navigation information. Primary users are national meteorological centres, universities, private forecasters, and television broadcasters.

HRI broadcasts are in the frequency sub-band 1 690-1 698 MHz with centre frequencies at 1 694.5 MHz and 1 691 MHz. The bandwidth is 660 kHz; the figure of merit of reception stations is 10.5 dB/K; typical antenna diameters are 3 m; and minimum antenna elevation is 3°. The HRI service will be replaced by a digital high rate information transmission (HRIT) service on second-generation MetSat systems.

#### 2.2.2.2 S-VISSR

The stretched visible infrared spin scan radiometer (S-VISSR) service is operated by the following satellite systems:

– GMS (Japan)

– FY-2 (China).

Data observed by the VISSR sensors are transmitted to the main operations ground stations of the individual satellite 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. Typical bandwidth for the S-VISSR transmissions is around 6 MHz. The figure of merit of reception stations is 10.5 dB/K, and the minimum elevation angle of antennae is 5°.

The GMS S-VISSR service will initially be replaced by an upgraded version called HiRID when MTSAT becomes operational. HiRID will eventually be replaced by HRIT.

#### 2.2.2.3 GOES Variable (GVAR)

The United States' geostationary operational environmental satellites (GOES) transmit processed 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 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.

These S-VISSR and GVAR transmissions are disseminated for user stations via each satellite. S-VISSR transmissions are common to GMS-5 and FY-2, while GVAR transmissions are available only in the Americas (from U.S. GOES satellites, hence the name). While GVAR signals were originally intended for reception primarily by CDA stations, their usefulness has caused them to be received by a wide variety of users. In addition to the main users, the national meteorological agencies, these users include private weather forecasters as well as companies whose businesses depend on the knowledge of weather conditions in areas where forecasts are not generally available, e.g. in isolated landmasses and over the oceans. A number of vendors are known to be marketing GVAR and S-VISSR receivers to the public. Also, technologically capable individuals can readily assemble receivers from commercially available parts. Since receive-only stations usually need not be licensed or registered, there is no way to identify either the number or location of these stations.

#### 2.2.2.4 Weather facsimile

The weather facsimile (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). WEFAX services are operated by the following satellite systems:

– GOES-E (USA)

– GOES-W (USA)

– GMS (JAPAN)

– GOMS (Russia)

– METEOSAT (EUMETSAT)

– FY-2 (China).

WMO has registered several thousand 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. WEFAX reception stations are also known as secondary data user stations (SDUS) (METEOSAT and GMS) or LR-FAX Stations (FY-2).

The transmission of WEFAX services is in the sub-band 1 690-1 698 MHz. Most 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°, use antennas of 1.2 m diameter and correspond to 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. The analogue WEFAX service will be replaced by digital low rate information transmission (LRIT) service on second-generation meteorological satellite systems.

#### 2.2.2.5 Meteorological data distribution

The meteorological data distribution (MDD) service is unique to METEOSAT operations. It is a broadcast of four data channels with a data rate of 2 400 kbit/s each. Transmissions are in the 1 695.68-1 695.86 MHz band. There are hundreds of user stations, mainly in Europe and Africa. MDD user stations use antennas with 2.4 m diameter and require a figure of merit of 6 dB/K. Operations require a minimum elevation angle of 3°.

#### 2.2.2.6 Low rate information transmission

LRIT will be a new service provided by geostationary meteorological satellites for transmission to low cost user stations. This service is intended to replace the WEFAX service and will serve a similar user community. It is expected that there will be thousands of user stations called low rate user stations (LRUS).

Transmissions of LRIT will be in the sub-band 1 690-1 698 MHz with centre frequencies around 1 691 MHz. The bandwidth will be up to 200 kHz. User station antennas will have diameters around 1.8 m and will be operated with a minimum elevation angle of 3°. The figure of merit for LRUS will be 5-6 dB/K (GMS: 3 dB/K) depending on the user station location.

#### 2.2.2.7 High rate information transmission

HRIT service will be introduced on METEOSAT second generation satellites and Japanese MTSAT and will replace the present HRI service and S-VISSR. It can be expected that other satellite operators will adopt HRIT for their future satellite broadcast services. It can also be expected that several hundred of the high rate user stations (HRUS) and the MDUS will be operated worldwide. The user community will consist of major meteorological and climatological centres as well as universities and other user communities producing numerical products.

The HRIT service will operate in the sub-band 1 690-1 698 MHz. The antenna size for HRUS and MDUS will be 4 m and the minimum elevation angle will be 3°. The figure of merit for the same users stations will be 12-14 dB/K depending on the user station location.

#### 2.2.2.8 Geostationary operational meteorological satellite (GOMS)

The GOMS system of Russia transmits raw imagery data in the 7 450-7 550 MHz band in high resolution direct (HRD) format allowed for reception by any user. The signal bandwidth is 5 MHz. There are two types of receiving stations for reception of this data with antenna sizes of 3 m and 12 m.

### 2.2.3 Data collection platforms

Data collection platforms (DCPs) are operated on meteorological satellites for the collection of meteorological and other environmental data from remote DCPs. Transmissions from each DCP to a 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) are presently in test operation. Bandwidths of DCPs are 1.5 kHz or 3 kHz. Two types of DCP transmitters are operated, 5 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 40-52 dBm. Data collection systems are operated on the following geostationary meteorological satellite systems:

– GOES-E (USA)

– GOES-W (USA)

– METEOSAT (EUMETSAT)

– GOMS (Russia)

– MTSAT (Japan)

– FY-2 (China).

The DCPs reporting to geostationary MetSats use frequencies in the 401.7-402.4 MHz range, with 402-402.1 MHz for international use (33 channels of 3 kHz in width). The GOES satellites (USA) domestically assign frequencies in the range of 401.7 to 402 MHz, with METEOSAT (Europe) and GMS (Japan) using 402.1-402.4 MHz and GOMS (Russia) using the 401.7-402.4 MHz band (expected to be put into operations in 2003). By using narrow bands (as small as 1.5 kHz) and by staggering the reporting times, it is possible to receive data from a large number of these platforms. At present, there are slightly more than 11 000 GOES DCPs, with the number anticipated to more than double to as many as 23 000. Such increased use will possibly necessitate expanding spectrum usage to higher frequencies, moving toward 403 MHz for these reporting platforms.

## 2.3 MetSat service systems using non-GSO satellites

### 2.3.1 Raw image sensor data transmissions

Raw data from European polar orbiting meteorological satellites will be transmitted in the frequency band 7 750-7 850 MHz to main stations located at high latitudes. Normally there are up to 4 receiving stations serving such satellites systems. The transmissions will take place in bursts as each satellite passes its appropriate receiving station, with the transmitters switched off at other times. Systems are to be operated by the European Space Agency (ESA)/EUMETSAT beginning in 2003. Typical transmission bandwidth is to be 100 MHz and the receiving station $G/T = 32$ dB/K. Antenna patterns are to be in accordance with RR Appendix 7.

### 2.3.2 Data dissemination

#### 2.3.2.1 Automatic picture transmission

The automatic picture transmission (APT) service was introduced on US spacecraft in the 1960s and became the most successful direct broadcast service in the meteorological community. There are thousands of APT receiving stations 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. The APT service is supported by NOAA (USA) and by METEOR, Okean and Resurs-01#4 (Russia) satellites.

APT transmissions are based on an analogue modulation scheme. Transmissions are in the band 137-138 MHz, with typical bandwidths of 40-50 kHz but up to 175 kHz. Future APT broadcasts will be restricted to two sub-bands in the 137-138 MHz band: sub-bands 137-137.175 MHz, and 137.825-138 MHz.

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.

#### 2.3.2.2 Low resolution picture transmission

The low resolution picture transmission (LRPT) service is planned to replace the APT service in future generations on non-GSO MetSats. It will be based on digital transmission schemes and will make use of the same frequency bands as those currently used for APT. The bandwidth will also be up to 175 kHz. It is expected that most APT users will convert to LRPT, leading to thousands of user stations worldwide. LRPT will first be implemented by EUMETSAT on METOP/EPS satellites. It is expected that there will be LRPT services supported by USA, Russia, and China.

#### 2.3.2.3 High resolution picture transmission

The high resolution picture transmission (HRPT) service is currently provided by NOAA (USA) satellites and is intended to supply high-resolution imagery to the meteorological community. Russia also has plans to provide HRPT transmissions. Furthermore, there is an HRPT-like broadcast provided by Chinese satellites (see CHRPT below). HRPT transmissions are full time and can be received by any user station in the reception area of the satellite. There are hundreds of HRPT receiving stations worldwide registered with the WMO. Again, the caveat is necessary that this number is non 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.

HRPT transmissions are performed in the frequency band 1 696-1 710 MHz with signal bandwidths between 2.7 MHz and 4.5 MHz. User stations are equipped with tracking parabolic antennas typically 2.4-3 m in diameter. The minimum elevation angle for reception is 5°, though some stations operate below this level. The figure of merit for stations is 5 dB/K.

#### 2.3.2.3.1 Chinese HRPT

The main characteristics of Chinese HRPT (CHRPT) are similar to HRPT. The major difference is in the data rate of transmissions, which is double the amount of HRPT. The bandwidth of transmissions is within the range given for HRPT. CHRPT broadcasts are unique to FY-1 satellites.

#### 2.3.2.3.2 Advanced HRPT

The advanced HRPT (AHRPT) service is intended to replace HRPT on future meteorological satellites. It is planned to introduce this service on EUMETSAT METOP/EPS and PRC FY3 (also referred to as CHHRPT) satellites. Satellite operators may convert to this new service or may choose to continue HRPT transmissions for some time.

AHRPT transmissions will be in the 1 698-1 710 MHz band. The bandwidth will be 4.5 MHz. AHRPT reception stations will receive with minimum elevation angles of 5°. Antennae are parabolic with typical diameters of 2.4-3m. The figure of merit of stations will be 6.5 dB/K. CHHRPT will be operated at 1 704.5 MHz.

### 2.3.3 Data collection platforms

DCPs provide a variety of information used principally by governmental agencies but also by commercial interests. Such data include a number of environmental parameters for oceans, rivers, lakes, solid earth and atmosphere related to physical, chemical, and biological processes including tracking animal movement. Use by commercial interests is limited, but includes monitoring oil pipeline conditions in order to protect the environment. Alert DCPs are also employed to report emergencies and supply data for hazard/disaster recognition. The Data Collection System operated from non-geostationary meteorological satellites is called ARGOS. It is currently flown only on the NOAA polar-orbiting satellites. Expansion of ARGOS is scheduled with flights on ADEOS-2 (Japan) and on the new series of European polar-orbiting satellites, known as METOP and a new generation of Russian polar-orbiting satellites (METEOR-3M).

The allocation at 401-403 MHz for these DCPs was up-graded to primary at the World Radiocommunication Conference in 1997 (WRC-97). The ARGOS system uses 401.65 MHz as the centre frequency, employing bandwidths of up to 100 kHz, though many platforms (known as platform transmitter terminals) require only several kHz. Taking advantage of the nature of the orbits of polar-orbiting satellites, it is possible to accommodate many ARGOS platforms. Future estimates expect that the existing 3 800 platforms will grow to 8 700, requiring use of additional spectrum, perhaps lower in frequency, i.e. toward 401 MHz.

# CHAPTER 3

## METEOROLOGICAL AIDS SERVICE

Page

## 3 Introduction

The meteorological aids (MetAids) service is defined in RR No. 1.50 as a radiocommunication service used for meteorological, including hydrological, observations and exploration.

In practice, MetAids service usually provides the link between an *in situ* sensing system for meteorological variables 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.

### 3.1 Allocated RF bands

Existing allocations for the MetAids service (other than those governed by national footnotes) are as follows:

| Frequency band | Status | Other primary services in the band |
|---|---|---|
| 2 025-2 045 kHz | Secondary (Region 1) | FIXED, MOBILE |
| 27.5-28 MHz | PRIMARY | FIXED, MOBILE |
| 153-154 MHz | Secondary (Region 1) | FIXED, MOBILE |
| 400.15-401 MHz | PRIMARY | METEOROLOGICAL-SATELLITE (space-to-Earth)<br>MOBILE-SATELLITE (space-to-Earth)<br>SPACE RESEARCH (space-to-Earth) |
| 401-402 MHz | PRIMARY | SPACE OPERATION (space-to-Earth)<br>METEOROLOGICAL-SATELLITE (Earth-to-space)<br>EARTH EXPLORATION-SATELLITE (Earth-to-space) |
| 402-403 MHz | PRIMARY | METEOROLOGICAL-SATELLITE (Earth-to-space)<br>EARTH EXPLORATION-SATELLITE (Earth-to-space) |
| 403-406 MHz | PRIMARY | |
| 1 668.4-1 670 MHz | PRIMARY | FIXED, MOBILE,<br>RADIOASTRONOMY |
| 1 670-1 675 MHz | PRIMARY | FIXED, MOBILE<br>METEOROLOGICAL-SATELLITE (space-to-Earth) |
| 1 675-1 690 MHz | PRIMARY | FIXED, MOBILE<br>METEOROLOGICAL-SATELLITE (space-to-Earth)<br>MOBILE-SATELLITE (Earth-to-space) (Region 2 only) |
| 1 690-1 700 MHz | PRIMARY | METEOROLOGICAL-SATELLITE (space-to-Earth)<br>MOBILE-SATELLITE (Earth-to-space) (Region 2 only) |
| 35.2-36 GHz | PRIMARY | RADIOLOCATION |

This list includes the services that are also primary in bands used by the MetAids service. The allocations for other services place 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, 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

– 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 allowed by the RR because of national sharing agreements with other radiocommunication services, as noted earlier.

Reviews of MetAids service use between 1978 and 1988 showed commercially available radiosonde systems operating in the WMO network at radiofrequencies between 27.5-28 MHz, 400.15-406 MHz and 1 668.4-1 700 MHz. Subsequently, routine radiosonde use in the band 27.5-28 MHz ceased because of problems with radiofrequency interference from other services. The reasons for the continued use of two MetAids service bands is discussed in a later section, once the systems in use have been discussed in more detail.

## 3.2 Meteorological functions of the MetAids service

Accurate measurements of the variations with height in atmospheric temperature, 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. 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. 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. The height to which regular observations are required varies to some extent with the application and geographical location. 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 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. 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 on falling to earth after the balloon bursts.

Every day more than 1 400 radiosondes are launched in the WMO GOS network. 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 pilotless aircraft<br>(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 |

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 is used as the standard for network studies on the 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.

## 3.3 Examples of MetAids sensing systems

### 3.3.1 Radiosondes

As many as 800 000 radiosondes are flown on balloons each year worldwide, see Figs. 3-1 and 3-2. 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.

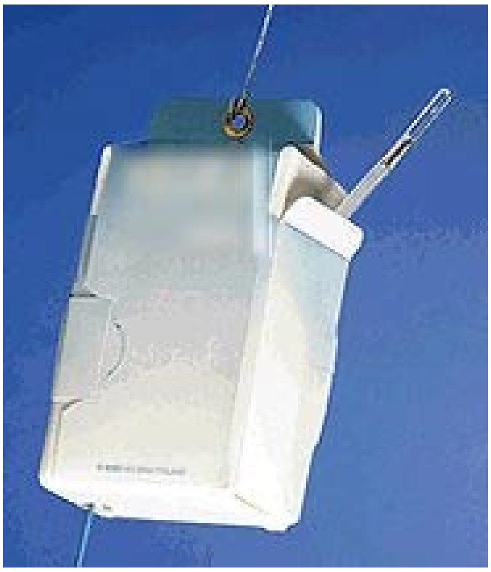
FIGURE 3-1

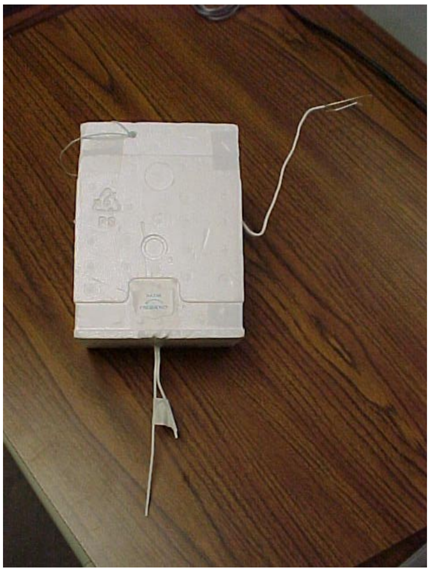
**A radiosonde flight train**

Meteo-031

FIGURE 3-2

**Radiosondes**





Meteo-032

A typical radiosonde contains several major components: a transmitter, sensor pack, battery, and a navigational aids (NAVAID) receiver see Fig. 3-3. The transmitter transmits the data to the receiving station. The sensor pack contains the sensors that measure the atmospheric conditions such as temperature, pressure, humidity, ozone or ionising radiation. The sensor pack also encodes the sensor values sufficiently to transmit them to the ground station. If the radiosonde relies on NAVAID signals for wind measurement, the radiosonde will also contain a NAVAID receiver for the type of signals used. Global positioning system (GPS), LORAN and VLF signals are used by NAVAID radiosondes. Radiosondes rely on batteries for power. The batteries are usually water-activated, manufactured specifically for radiosonde use, since commercially available alkaline batteries cannot operate at air temperatures that can reach –90° C.

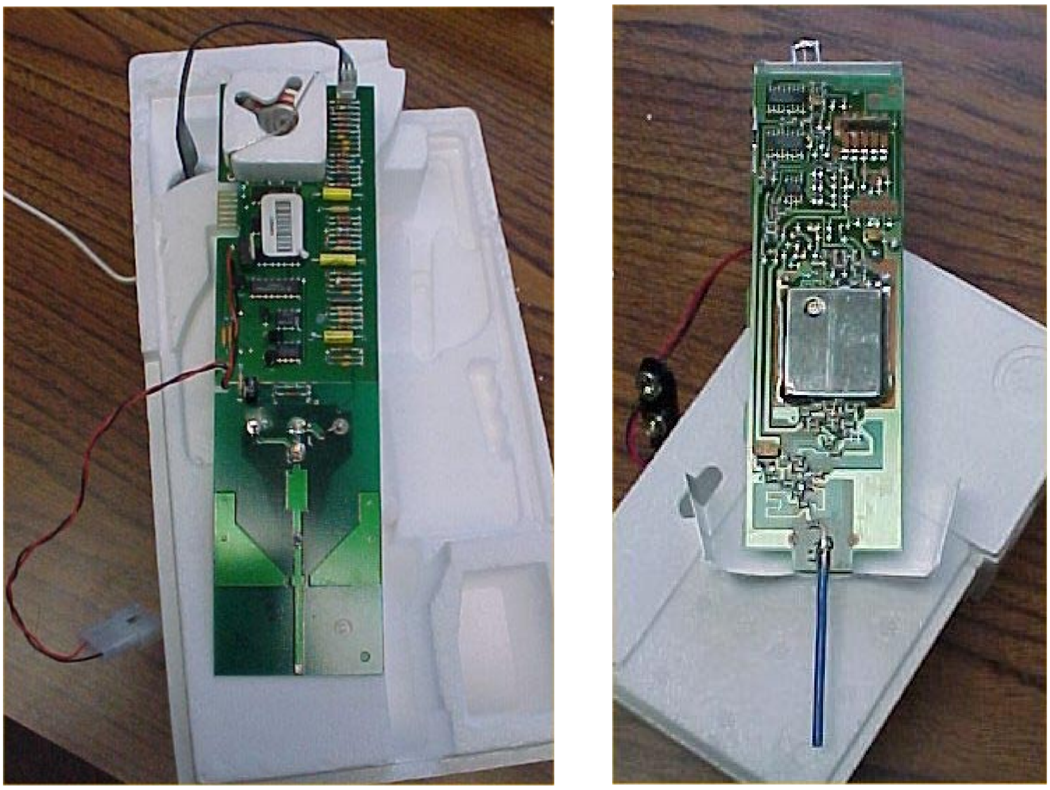
A typical cost breakdown of a radiosonde is 20% to 30% for the transmitter, 45% to 60% for the sensor pack, 20% to 50% for the NAVAID receiver (if required) and 15% to 25 % for the battery. Some radiosonde transmitters exhibit relatively poor characteristics in comparison to most other radio services. The general use of transmitters with poor stability and large bandwidth emissions is due to their relatively low cost. For the same reason that processing power is minimized on the radiosonde, use of highly stable transmitters has usually been avoided until the technology becomes available at an appropriate cost. However, the operating conditions in some national networks already require the use of narrow-band high stability transmitters.

### 3.3.2 Dropsondes

Dropsondes have components similar to radiosondes, but the assembled system is modified so that it 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 NAVAIDS (currently GPS) 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 12 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.

FIGURE 3-3

**Radiosonde electronics**



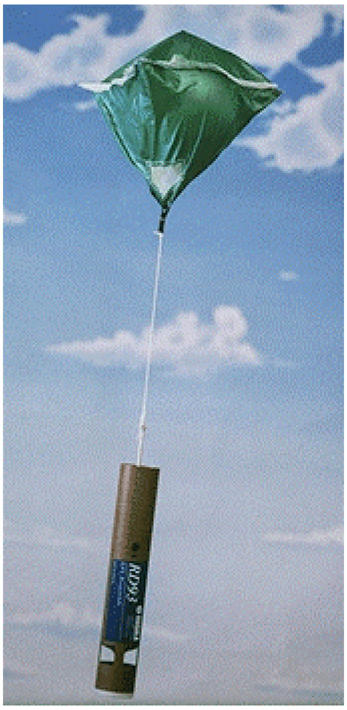
Meteo-033

### 3.3.3 Rocketsondes

Rocketsondes are a more specialized MetAids system. Like the dropsondes, they 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 NAVAIDS 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 3-4

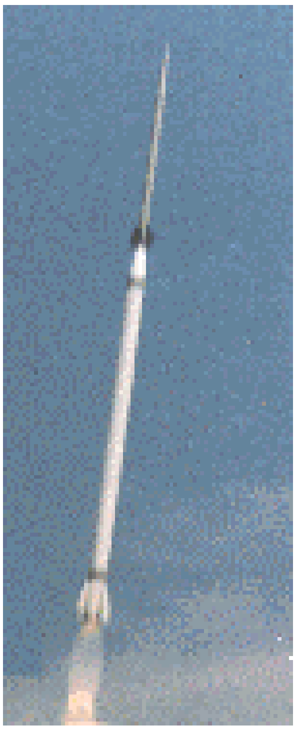
**A dropsonde**



Meteo-034

FIGURE 3-5

**A rocketsonde**



Meteo-035

## 3.4 Factors influencing the characteristics of the MetAids systems

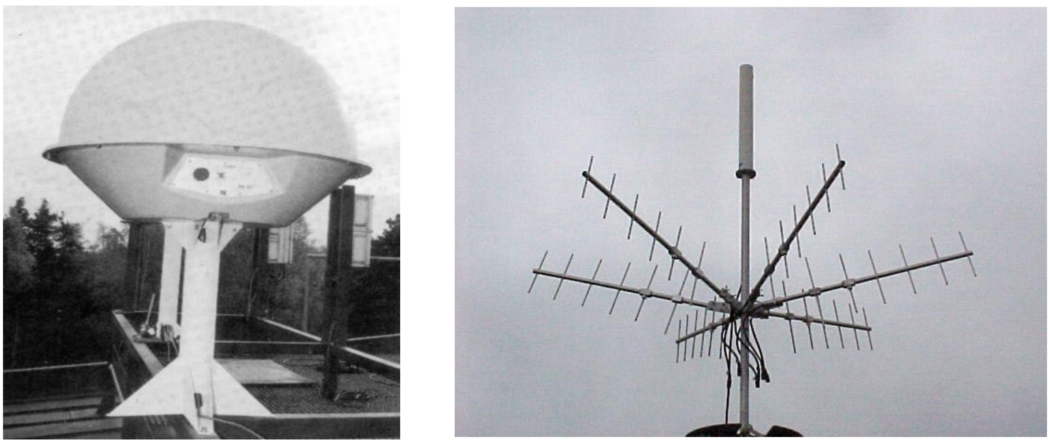
MetAids systems are comprised of several basic radiocommunication components. The ground portion of the system typically contains an antenna/receiver system and a signal processing system. Recommendation ITU-R SA.1165 – Technical characteristics and performance antenna for radiosonde systems in the meteorological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

### 3.4.1 Ground-based receiver antenna system

MetAids 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 and 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 401-406 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 401-406 MHz range from 0 dBi to 10 dBi.

FIGURE 3-6

**Omni-directional antenna and directional systems (401-406 MHz)**



Meteo-036

Wind measurement is usually accomplished through RDF in the 1 668.4-1 700 MHz band. 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-037

### 3.4.2 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. Most MetAids do not transmit the actual meteorological values (pressure, temperature, humidity, ozone, etc.) to the receiving station. To minimize the cost of processing on the MetAid, the electronic characteristic of the capacitive or resistive sensor is transmitted. The signal processing system then applies the capacitive and/or resistive sensor values and sensor calibration values, to a polynomial to calculate the meteorological parameter. Systems that use NAVAIDS for wind measurement also defer the processing of the NAVAID signal to the signal processing system as much as possible. Some MetAids simply receive the NAVAID signal and retransmit it to the receiving station for processing in the signal processing system. The transmission of raw data to the ground station increases the RF link data rate above what would be required if processing were performed on the MetAid. This approach is necessary, as it is not cost effective to place the processing power on each expendable device.

### 3.4.3 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. 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) has not been widespread so far, as many available products used for wireless communications do not meet the operating environment conditions or do not operate in the MetAids bands.

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. It is worth noting that no collision between a radiosonde and an aircraft has ever been reported. 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 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. Typically, radiosondes are housed in a foam or paperboard 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 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 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.

## 3.5 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.

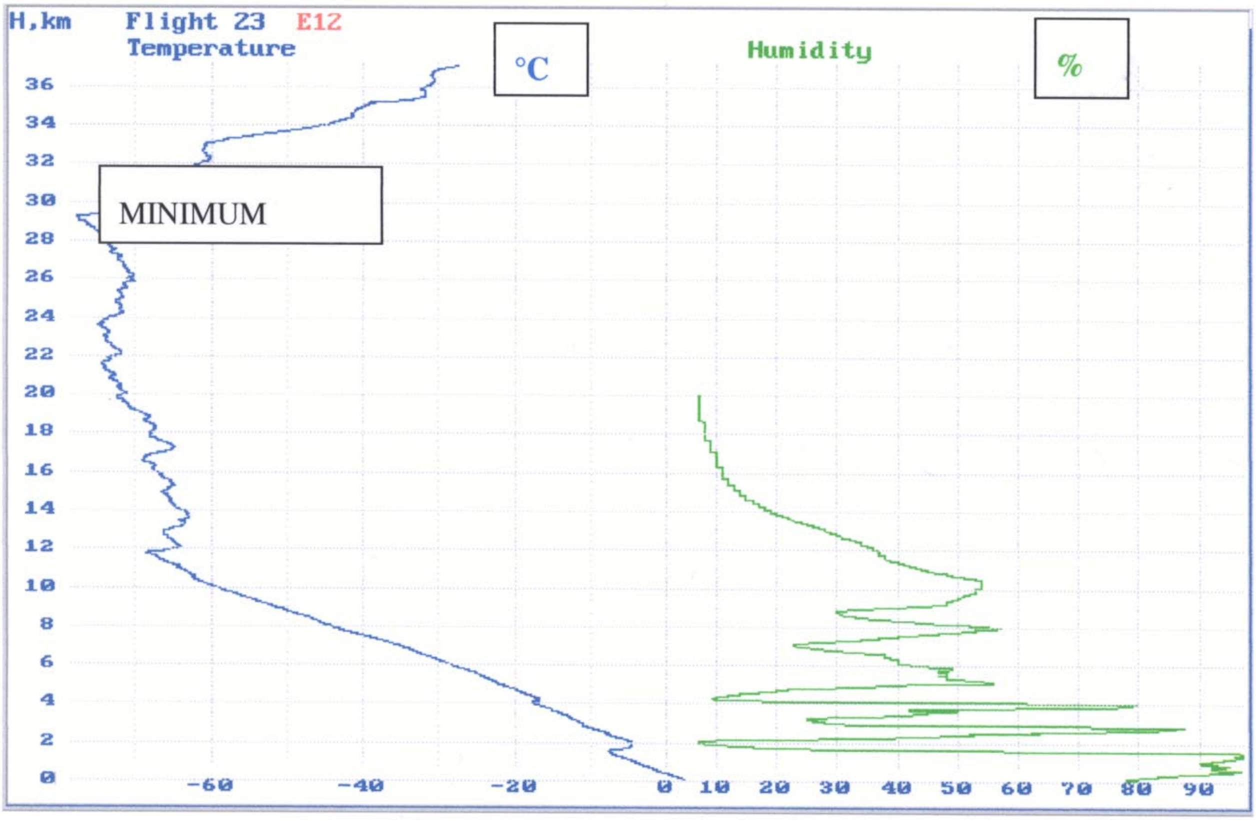
Figure 3-8 shows temperature and relative humidity measurements as a function of height, in a measurement from a climate monitoring site at 60° N in the UK (Lerwick, Shetland Islands, 23 January 2000). Radiosonde temperature measurements have small errors, less than 0.5° C at heights up to 28 km, and 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 for civilian and strategic purposes.

The balloons lifting the radiosondes are designed to provide optimum burst heights 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, 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 errors in the 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**



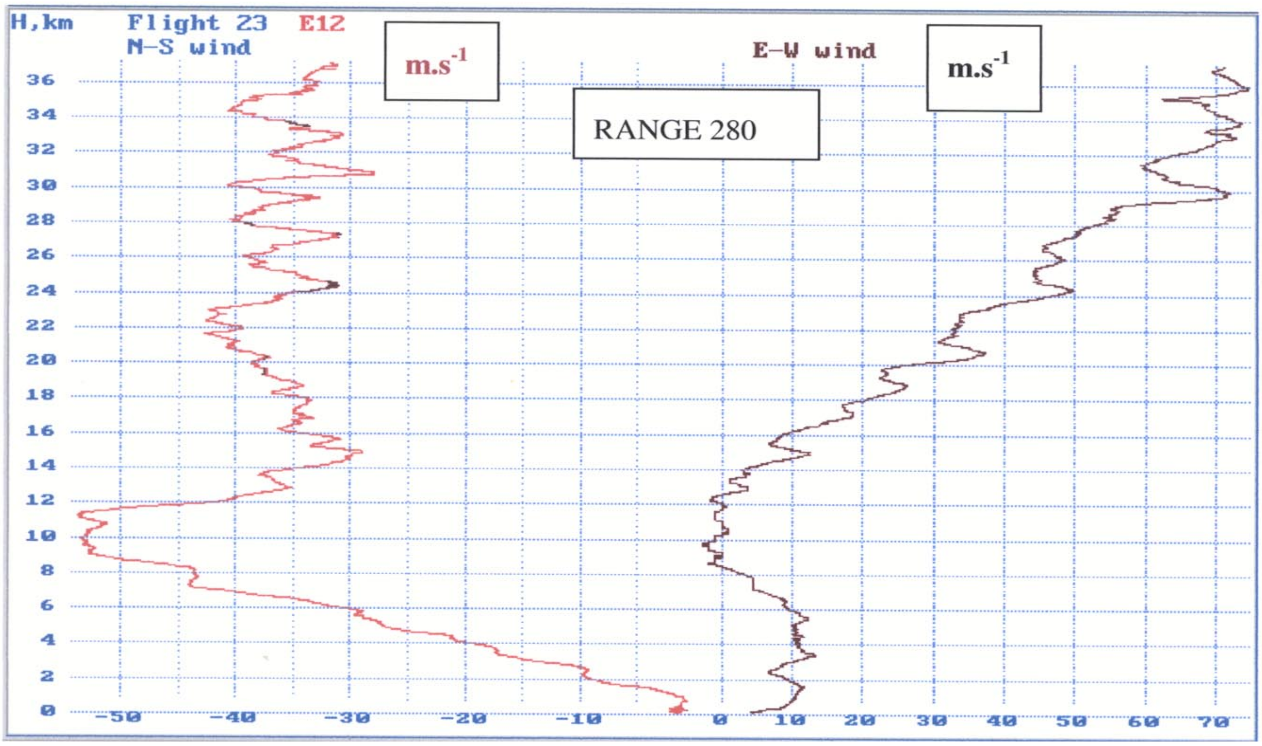

Meteo-038

The minimum temperature in Fig. 3-8 occurred at about 29 km, and was associated with even colder air to the north of the station. The temperature had fallen close to the conditions needed to initiate the chemical mechanisms that destroy ozone in the northern winter. The pronounced rise in temperature above 29 km results from significant warming generated by upper atmospheric motion in the northern winter.

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 optimum. 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.

FIGURE 3-9

**Wind measurements by radiosonde**

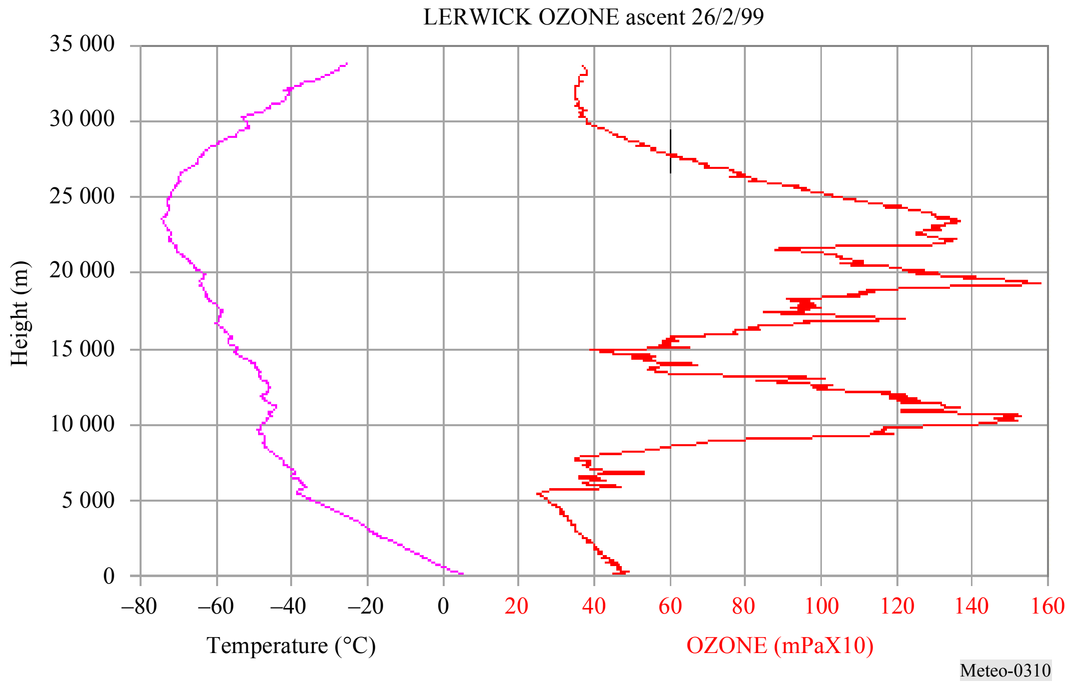



Meteo-039

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. 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 or be caused by decay associated with chemical pollution.

FIGURE 3-10

**Measurement of ozone distribution in the vertical uses an ozonesonde**




## 3.6 Reasons for national variations in MetAids service operations

### 3.6.1 Variation in available technology

While most radiosonde systems are purchased from a limited number of international commercial suppliers, the economic 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 round the world is less than 10 years old, some of the national systems are still based on technology used 30-40 years ago. 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.

### 3.6.2 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 navigation signal, either Loran-C or GPS. 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; while in others the radiosonde must be tracked down to elevations lower than 5° above the horizon at ranges in excess of 200 km.

Where balloon elevations remain high (particularly if elevations lower than 15° 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 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.

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 radiosondes operating in the 401-406 MHz band. The automated system has to have a minimum of two available radiosondes, preset 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 401 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.

#### 3.6.3 Differences in network density

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 are unlikely to have the resources to operate a large number of stations or procure high stability narrow-band transmitters.

#### 3.6.4 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 401-406 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, however, where the density of stations is not extremely high, and 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. In 1998, the WMO held a meeting of experts on MetAids radio frequency characteristics. This group concluded that the entire 401-406 MHz band is required for MetAids operation for the foreseeable future. It was accepted that co-channel sharing with the satellite services proposed between 400.15 MHz and 401 MHz would not be possible for standard radiosonde operations.

### 3.6.5 Use of the 1 688.4-1 700 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 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 kept in mind that only a portion of the band is usually available. Many countries that use this band are able to 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. The WMO held a meeting of experts on meteorological aids radio frequency characteristics in 1998. This group concluded that 12 MHz of spectrum would be required for MetAids operations in this band for the foreseeable future. This assessment was based on peak requirements, and there may be a number of countries where less spectrum is required. With this in mind, subsequent WMO meetings have recommended that the Metaids service be strongly protected within the 1 675-1 683 MHz sub-band.

### 3.6.6 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 (GPS, LORAN or VLF) 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. RDF MetAids eliminate the need for radio navigation circuitry. This reduces the cost of the expendable devices. Some countries also have the requirement that their MetAids systems be independent of international NAVAID systems, as these systems may not always be available.

### 3.7 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 started to require improvements in the RF characteristics as well.

#### 3.7.1 GPS windfinding

Implementation of GPS on radiosondes for purposes of measuring winds should lead to significant improvements in the spectrum efficiency of NAVAID radiosondes. In most countries, it will lead to a significant improvement in the accuracy of upper wind measurements. GPS windfinding requires that a significant amount of GPS-related data be transmitted from the device to the ground, increasing the data rate requirements, and as a result, expanding the transmitter bandwidth and increasing battery consumption compared to non-NAVAID radiosondes. Processing the full GPS solution on the device may not be feasible since differential correction must be applied to eliminate errors caused by propagation conditions and other factors. This differential correction can only be applied at the receiving station. Although this type of radiosonde has been in use since 1997, WMO is still working with the manufacturers four years later to eliminate problems that have hindered operations. Other uses by meteorologists of the GPS radionavigation service are discussed in Chapter 6.

#### 3.7.2 Commercially available transmitter integrated circuits

Use of commercially available wireless communications transmitter integrated circuits (ICs) has not been widespread to date, for several reasons. First, there are a limited number of ICs available that extend into MetAids frequency bands. The ICs that are available typically are not designed for operation at the low temperature extremes required of MetAids. Development and production of MetAid-specific application specific ICs (ASICs) that meet the frequency, power and environmental requirements has not yet proven to be cost effective due to the relatively low numbers required per year. However, in he future, the production costs for ASICs are expected to decrease allowing cost-effective production of smaller lots of ASICs for low volume applications such as MetAids.

#### 3.7.3 Increased MetAids network density

The WMO has established goals to increase the density of MetAids networks. As a result, MetAids operators have been forced to improve MetAids radio frequency characteristics to eliminate adjacent station interference.

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# CHAPTER 4

# METEOROLOGICAL RADARS

Page

## 4.1 Introduction

Meteorological radars are among the best-known life savers in meteorology. It is through the use of radar that we are able to predict the formation of hurricanes, tornadoes, and other severe weather and to track the course of storms on their destructive paths. Modern radar lets us track the path of storms large and small and tells us whether to expect precipitation and at what rates. The rain rate may indicate the potential for flash floods. It lets us know whether high winds and lightning are likely. Meteorological radars operate within the "Radiolocation service".

This Chapter discusses ground-based radars commonly used in meteorology. The first and most familiar is the rotating radar, which provides data from within a roughly circular area centred on its own location. Commonly referred to as weather radars, these devices are familiar to many, for their output is commonly shown in television weather forecasts. The radio frequency bands used by weather radars are located around 2.8 GHz, 5.6 GHz, 9.4 GHz and 35.6 GHz.

A more recent development is the wind profiler radar (WPR), which provides data from a roughly cone-shaped volume directly overhead. The WPR is a relatively recent development, having come into common use only within the past decade. It measures wind velocity – speed and direction – as a function of height above ground. If properly equipped, a WPR can also measure air temperature (as a function of height). The radio frequency bands used by the WPR are located around 50 MHz, 400 MHz and 1 000 MHz.

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

All radars operate by emitting radio signals, which are reflected from a target that can be anything from a vehicle to raindrops to turbulence in the atmosphere. The return signal of weather radar is weak for several reasons. First, the signal must traverse the path twice, once from the radar to the target and again in the other direction. Secondly, the target 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, extremely sensitive receivers, and long signal integration times. Relatively "quiet" spectrum – absence of man-made electronic noise and interference – is also a critical requirement.

### 4.1.1 General

Meteorological radars are typically volume scanning, pencil beam radars which detect and measure both hydrometeor intensities and velocities of hail, snow, clouds, and especially rain. The radar reflectivity of rain is related to the following parameters: drop size distribution, relative permittivity of the medium under consideration, and radar wavelength. Meteorological radars are also capable of wind measurements. The following three different types of radars can carry out these functions:

1. Doppler weather radars where the hydrometeor is being used as a tracer.

2. Balloon-tracking radars, which provide the wind vector in terms of velocity and direction.

3. WPRs, which detects the air refractive index turbulent variation and uses it as a tracer.

### 4.1.2 Radar equation

An easy-to-understand formulation of the radar equation can be written as in equation (4-1). This shows the different contributions to the received power i.e.: the radar constant, the target reflectivity and the atmospheric attenuation mostly due to clouds and rain. In this relationship, the target being an echo that fluctuates, the reflectivity of the rain $\eta$ remains an average value that results from *the time-space integration process* within the radar cell during the dwell time:

$$P_r = \underbrace{\frac{P_t \cdot A_e^2 \cdot \lambda^2 \cdot c \cdot \tau \cdot \theta^2 \cdot l_s}{45}}_{\textit{radar performance}} \cdot \underbrace{\frac{\eta}{r^2}}_{\textit{target reflectivity}} \cdot \underbrace{\frac{1}{L^2}}_{\textit{path loss}} \tag{4-1}$$

where:

$P_r$: received return power
$P_t$: transmitter output power
$A_e$: antenna effective aperture
$l_s$: radar system losses
$\lambda$: wavelength
$c$: speed of light
$\theta$: antenna 3 dB beamwidth
$\tau$: pulse width
$\eta$: reflectivity
$r$: range to target
$L$: path loss includint atmospheric attenuation.

Equation (4-1) can be applied to a distributed target when the following assumptions are satisfied:

– the target occupies the entire volume of the pulse
– it consists of spherical particles or particles which can be approximated by spheres
– the size of the particles satisfies the Rayleigh condition
– the dielectric constant $|K|^2$ and the size distribution of the scatterers are homogeneous in the volume $V$ considered
– the antenna beam is approximately Gaussian
– beam polarization is linear
– the effects of multiple scattering are neglected.

## 4.2 Rotating weather radars

### 4.2.1 User requirements

The main user requirement for the weather radar is to detect solid and liquid precipitation, and when possible, to measure the rate of precipitation and the component of velocity towards the radar.

### 4.2.2 Operational aspects of reflectivity

The reflectivity $\eta$ of rain is related to the water relative permittivity $\varepsilon_r$, the drop diameter $D$, and the wavelength $\lambda$. For raindrops contained within the volume $V$ under consideration, the reflectivity can be expressed as equation (4-2):

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

where $|K|^2$ is 0.93 for liquid water and 0.18 for ice.

The reflectivity factor $Z$, independent of $\lambda$, is defined as follows:

$$Z = \sum_{j} D_j^6 / V \qquad (4\text{-}3)$$

$Z$ is usually expressed as $dB_Z = 10 \log Z$ ($mm^6/m^3$).

Then, for water droplets:

$$\eta = \frac{285\, Z}{\lambda^4} \qquad (4\text{-}4)$$

NOTE – This expression is valid only within the Rayleigh scattering domain, i.e. for:

$$D \leq \frac{\lambda}{20} \qquad (4\text{-}5)$$

The reflectivity, $Z$ (expressed in $dB_z$) and the rainfall rate, $R$ (expressed in mm/h) are related by:

$$Z = a \cdot R^b \qquad (4\text{-}6)$$

Both $a$ and $b$ depend upon the drop size distribution (DSD) which varies with the type and intensity of rain. A common expression, established by Marshall-Palmer in 1948, is based on an exponential DSD and is written as:

$$Z = 200 \cdot R^{1.6} \qquad (4\text{-}7)$$

where $Z$ and $R$ are expressed in $mm^6/m^3$ and in mm/h, respectively.

### 4.2.3 Weather radar networks

The main limitation of the weather radar is its relatively short range as a consequence of the curvature of the Earth. To overcome this constraint, multiple radars are generally equally spaced into distributed networks operating 24 h a day. These networks often cover 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.

### 4.2.4 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 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 or travelling wave tubes (TWTs). Conventional radar spectrum phase purity is currently being limited by magnetron technology. However, the existing magnetrons can economically deliver high average power to increase the signal to noise ratio.

### 4.2.5 Multiparameter radars

Polarimetric radar technology permits the identification of scatterers by remotely sensing their shapes. Polarimetric weather radar has been proposed as a tool for hydrometeor identification and for improving the reliability and accuracy of rainfall rates needed for hydrological applications. In fact, falling raindrops tend to flatten, the flatness increasing with drop size. Combining reflectivity and phase measurements using two polarizations, horizontal (h) and vertical (v), enables a better assessment of the coefficients *a* and *b* of the *Z-R* relationship.

Some recently developed algorithms, based on differential reflectivity ratio $Z_h/Z_v$ and differential phase $\varphi_h - \varphi_v$, taking into the account the differential attenuation as well, are considered very promising for yielding 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 proposed to discriminate between rain and snow and to quantify liquid water and ice in clouds using differential attenuation measurements made with dual band radar.

### 4.2.6 Fixed echo elimination

The so-called fixed echo includes several hidden fixed component; one that includes low frequency scattering, and a second that includes higher frequencies (due to vegetation ruffled by the wind). 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 high enough to fall above the cut-off frequency of the Doppler filter.

– Statistical filtering based on the difference between the variances of rain and ground clutter reflectivity. The statistical filtering process is efficient even when the rain radial velocity is null (tangential rain).

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

### 4.2.7 Present and future spectrum requirements

The choice of wavelength $\lambda$ results from a trade-off between the reflectivity, which varies as $\lambda^{-4}$, and attenuation, which decreases as $\lambda$ increases to become negligible at decimetric wavelengths. For example, the Ka band (8.6 mm) is well suited for detecting small water drops, which occur in non-precipitating clouds ($\leq$ 200 µm). On the other hand, the S band (10 cm) is chosen for detecting heavy rain at very long ranges (up to 300 km) in tropical and temperate climates.

C band (5.4 cm) is sometimes preferred for use in temperate climates to detect the rain at long ranges (up to 300 km), but in fact, the rainfall rate can be successfully measured only to ranges of about 100 km.

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 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 velocity that the radar can measure. In the design of the radar, the designer is limited by the unambiguous range-velocity product, defined as:

$$R_m \cdot V_m = c\frac{\lambda}{8} \qquad (4\text{-}8)$$

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 ($3 \times 10^8$ m/s)

$\lambda$: 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.

Other discrete wavelengths used by meteorological radars are selected from radio frequency bands generally used for defence and air route surveillance radars. Wavelengths may differ slightly from one country to another. Table 4-1 shows the significant parameters of typical weather radars.

TABLE 4-1

**Radar system parameters**

| Radar system parameters | S band | C band | X band | Ka band |
|---|---|---|---|---|
| Instrumental range related to the radar PRF (km) | 600 | 450 | 200 | 150 |
| Maximum range to detect = 0 $dB_z$ in clear weather (km) | 300 | 300 | 150 | 80 |
| Maximum range to carry out a reliable measurement of $Z$ with moderate attenuation (km) | 150 | 125 | 100 | 40 |
| ITU band (GHz) | 2.7-2.9 | 5.6-5.65 | 9.3-9.5 | 35.2-36 |
| Principal Radio Regulations footnote No. | 5.423 | 5.452 | 5.475 | |
| Maximum occupied band (MHz) (between the zeroes of the sin $x/x$ function) | 4 | 4 | 4 | 2 |
| Pulse peak power: Magnetron (kW) | 1 000 | 250 | 100 | 100 |
| Pulse peak power: Klystron (kW) | 1 200 | 250 | 8 | not used |
| Pulse repetition frequency: Magnetron (Hz) | 250-1 200 | 250-1 200 | 1 000 | 1 000 |
| Pulse repetition frequency: Klystron (Hz) | 0-4 000 | 0-4 000 | 0-10 000 | not used |
| Pulse width: Magnetron (μs) | 0.8-2 | 0.8-2 | 1 | 1 |
| Pulse width: Klystron (μs) | 0.5-8 | 0.5-20 | 0.5-30 | not used |

TABLE 4-1 (*end*)

| Radar system parameters | S band | C band | X band | Ka band |
|---|---|---|---|---|
| Duty cycle: Magnetron (%) | $10^{-3}$ | $10^{-3}$ | $10^{-3}$ | $10^{-3}$ |
| Duty cycle: Klystron (%) | $2 \times 10^{-3}$ | $6 \times 10^{-3}$ | $3 \times 10^{-3}$ | not used |
| Average transmitted power: Magnetron (W) | 1 000 | 250 | 100 | 100 |
| Average transmitted power: Klystron (W) | 2 500 | 1 500 | 240 | not used |
| Antenna diameter (m) | 4-8 | 4 | 2 | 1.5 |
| Main beam antenna gain (dBi) | 39-45 | 44 | 43 | 50 |
| –3 dB beamwidth (degrees) | 2-1 | 1 | 1.2 | 0.4 |
| Sidelobes (dBc) | –25 to –35 | –25 to –35 | –25 to –30 | –25 |

*Note on the transmitted frequency spectrum*: If the transmitted pulse is rectangular of width $\tau$, the frequency spectrum shows a sin $x/x$ dependence of $x = \pi F \tau$ with the following well-known characteristics:

Half power width: $0.88/\tau$

First zeros at: $\pm 1/\tau$

First sidelobes at: $\pm 1.43/\tau$

Peak sidelobe levels decrease as: $1/x$.

If the pulse shape is approximately trapezoidal with rise and fall times $\Delta t$, the frequency spectrum may differ from sin $x/x$, and the sidelobe peaks may decrease faster than $1/x$ – as fast as $1/x^2$. However, for $\Delta t < 0.1\tau$, the spectrum is not very different from sin $x/x$ except for the sidelobes far from the centre frequency, which are significantly smaller.

Values are given for two types of different technologies: magnetrons and klystrons or 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.

### 4.2.8 Vulnerabilities of radars

A weather radar operates 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 (in the case of a pulsed radar.) 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 borne in mind 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 large transmitter powers and highly sensitive receivers, radars are extremely vulnerable to noise and interference.

### 4.2.9 Vulnerabilities of systems sharing with radars

As noted above, the transmitter power and antenna gain of weather radars are typically quite high to compensate for extended path lengths. This tends to create an extended range over which a radar can interfere with co-channel systems (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.

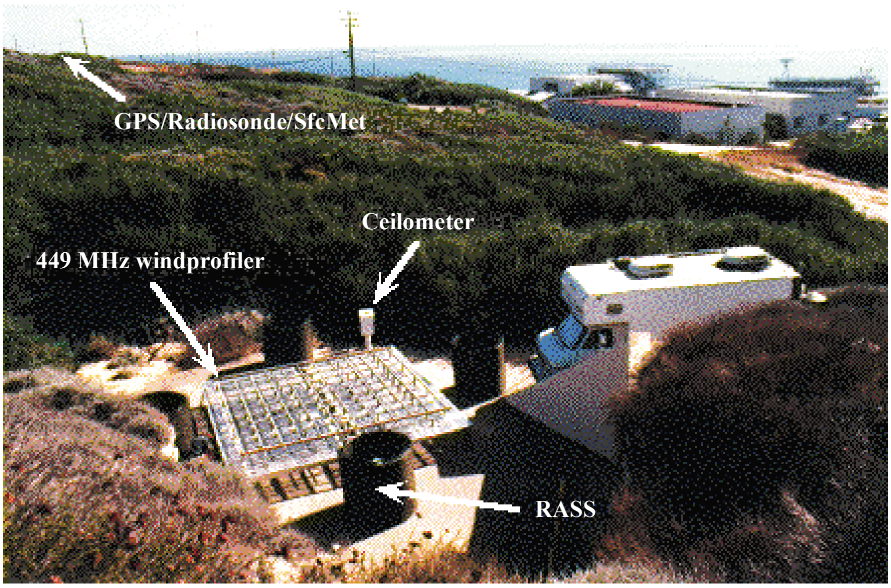
## 4.3 Wind profiler radars

### 4.3.1 User requirements

WPRs are used to obtain the vertical profiles of the wind over an unattended and sometimes remote site by detecting the tiny fraction of emitted power backscattered by turbulence in the clear atmosphere. User requirements for temporal and vertical resolution and height coverage affect the operating power, bandwidth, and centre frequency. Figure 4-1 shows a wind profiler radar installation.

FIGURE 4-1

**NOAA wind profiler at Point Loma, California, USA**




Meteo-041

Profilers can also determine air temperature as a function of height. Often termed a radar acoustic sounding system (RASS), this technique uses large loudspeakers located at the antenna to emit sound waves along the path of the vertical radar beam. The sound frequency is chosen to present an acoustic wavelength, which results in strong reflections of the radar signal at its operating frequency, allowing the radar to track the sound wave as it propagates upward. Since the speed of sound is a function of air temperature, measuring the speed of the acoustic wave permits the air temperature to be derived as a function of height above ground. A good way to examine the impact of user requirements upon wind profiler operating parameters and design is to consider the following equation rewritten from [Gossard and Strauch, 1983]:

$$SNR = \text{const} \; \frac{\overline{P}_t \, A_e \, \Delta_z \, \lambda^{1/6} \, t_{obs}^{1/2}}{T_{sys}} \; \frac{C_n^2}{z^2} \qquad (4\text{-}9)$$

where:

$\overline{P}_t$: average transmitted power

$A_e$: effective aperture

$\Delta_z$: height resolution

$z$: height

$\lambda$: wavelength

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

$T_{sys}$: system noise temperature

$C_n^2$: structure parameter.

In this equation, the structure parameter is independent of frequency but a strong function of height. Nearly all the frequency dependence is contained in the wavelength factor, but the system noise temperature of a well-designed radar receiver includes a significant contribution from cosmic noise at low frequencies. This equation is also valid only in the inertial sub-range of atmospheric turbulence, effectively limiting the choice of wind profiler radar wavelengths to the range of about 10-0.2 m (30 to 1 500 MHz). Note that turbulence is rapidly dissipated as heat by viscosity outside the inertial sub-range, and at short wavelengths.

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

– large averaging times.

Other, and more practical, considerations will be discussed in § 4.3.2.

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 cases 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 not attractive options for improving performance.

In the case of antenna aperture, however, there is another factor to consider which establishes a minimum size. Multi-beam profilers operate by successively swinging the main beam to two or four orthogonal azimuths at elevation angles of about 75° and often to the vertical to acquire data. The antenna beamwidth must be narrow enough to delineate the two, four or five 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 (4-10):

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

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 Missile 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. International radiolocation allocations exist in the band:

– 138-144 MHz on a permitted basis in Region 2;

– 223-230 MHz in Region 3 on a secondary basis;

– 420-430 and 440-450 MHz in all Regions on a secondary basis;

– 430-440 MHz in all Regions on a primary basis;

– 890-942 MHz in all Regions on a secondary basis;

– 1 215-1 300 MHz in all Regions on a primary basis; and

– 1 350-1 400 MHz in all Regions on a primary basis.

Wind profiler radars are currently operated in all of these bands except 138-144 MHz and near 404 MHz and 472 MHz. Resolution 217 (WRC-97) noted:

"... a request to ITU from the Secretary-General of the World Meteorological Organization in May 1989, for advice and assistance in the identification of appropriate frequencies near 50 MHz, 400 MHz, and 1 000 MHz in order to accommodate allocations and assignments for wind profiler radars" and resolved:

"... 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;" and

"... to urge administrations not to implement wind profiler radars in the band 400.15-406 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 250 m at low altitudes and 1 000 m at high altitudes using antennas with about 32 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.

Adding a third, very low altitude, mode would permit lowering the lowest range gate from 0.5 km to 0.25 km and possibly reducing the vertical resolution to 150 m or 200 m while remaining within a 2 MHz necessary bandwidth. Profilers operating at 915 MHz and above 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 8 MHz or more.

#### 4.3.3 Present and future spectrum requirements

Wind profilers are ground-based systems with antenna heights of one or two metres 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. For the same reasons, profilers tend to be compatible with most ground-based services. Resolution 217 (WRC-97) provides an adequate selection of radio-frequency spectrum, 2 MHz or 3 MHz of bandwidth are required near 400 MHz, 8 MHz or 10 MHz near 1 000 MHz.

#### 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. A network constructed before these bands became available was built in the meteorological band 400.1-406 MHz and resulted in interference to COSPAS-SARSAT operating in the band 406-406.1 MHz. The interference resulted in a recommendation by WRC-97 that this band not be used for future profilers. The administration which built this experimental system is constructing new profilers in an approved band, but the efforts made to make the 400 MHz system compatible resulted in considerable information regarding profiler compatibility issues. 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. For example, an amateur mobile radio, tuned to the centre frequency of the radar has been able to detect an audible WPR signal out to 3 km over a grassy plain.

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. As an example, early wind profilers in the United States of America were built using 404.37 MHz because at that time no appropriately allocated bands were available. At first, 404 MHz WPR signals were detected in SARSAT receivers operating in the band 406-406.1 MHz and carried by satellites in an 850 km orbit. Subsequent efforts to alleviate this problem 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 effect 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° above the profiler’s horizon. (There being only a few of these satellites, this 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 noted above, current ITU-R Recommendations provide spectrum to be used for WPRs. The use of other bands, e.g. 400.15-406 MHz for WPR is not recommended. The same techniques used to ameliorate interference to satellites in this band are, however, applicable in other bands as well.

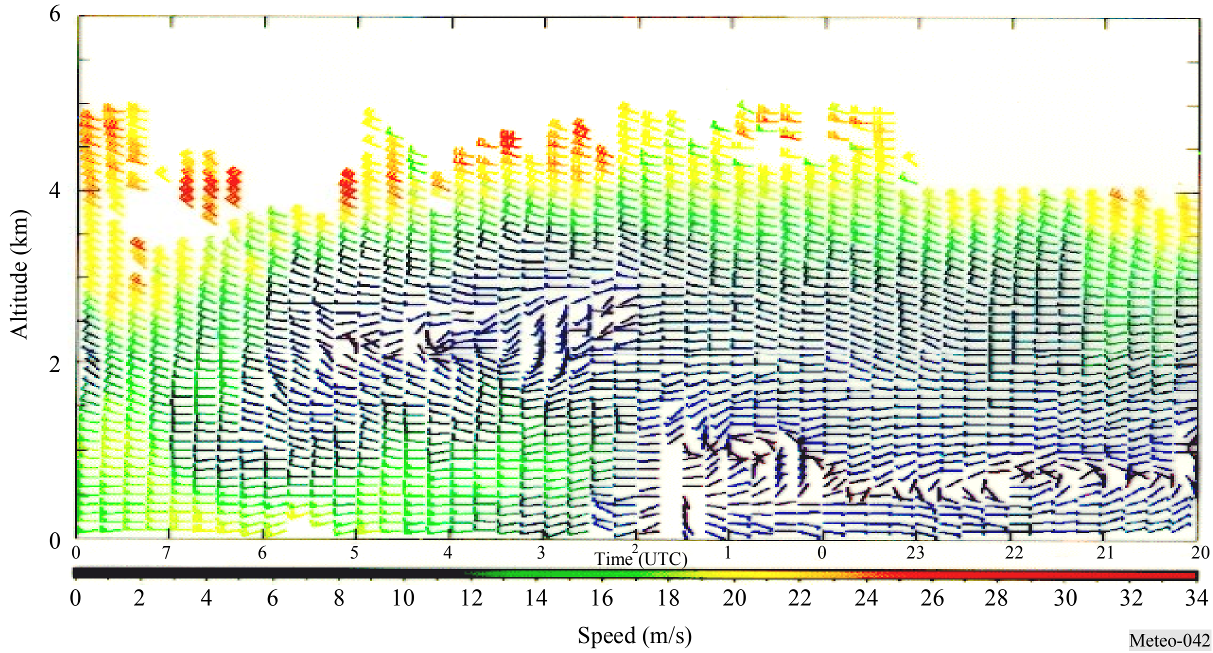
A NOAA mobile profiling system operating at 924 MHz produced the plot of wind velocity vs. altitude (see Fig. 4-2). The orientation of each flag represents wind direction as a function of altitude (vertical axis) and time (horizontal axis), while its colour represents wind speed. NOAA is currently developing a ship-borne profiler. See http://www4.etl.noaa.gov/.

### 4.3.5 1.3 GHz band wind profiler network operated by JMA

The Japan Meteorological Agency (JMA) has recently installed an upper-air observation network consisting of twenty-five 1.3 GHz band WPRs and a profiler control centre (PCC). They have been in full operation since April 2001. Together with existing radiosonde observation stations, JMA has obtained a dense upper-air observation network. The WPR network is continuously operated and wind data are provided for advanced numerical weather prediction and for now-casting.

FIGURE 4-2

**Wind velocity vs. altitude**




L-band WPRs (often called: boundary layer profilers) usually measure wind data at levels below a few kilometres. However, JMA WPRs collect data up to 5 km with the height resolution of 100-600 m, applying the pulse-compression technique, generating a high power transmission, and using a large-size antenna. All the WPRs are controlled from the PCC of the JMA headquarters in Tokyo. The main characteristics of the WPR are listed in Table 4-2.

TABLE 4-2

**Characteristics of 1.3 GHz band WPRs**

| | |
|---|---|
| Radiation frequency (MHz) | 1 357.5 |
| Occupied bandwidth (MHz) | 10 |
| Peak power (W) | 2 000 |
| Pulse-compression (bits) | 8 |
| Pulse length (µs) | Selectable in 0.67, 1.33, 2, 4 |
| Pulse repetition frequency (kHz) | Selectable in 5, 10, 15, 20 |
| Attenuation at 0° to 10° in elevation angle (dB) | –40 |

As a 2 m high clutter fence attenuates the side lobe level at 0° to 10° in elevation angle to 40 dB below the main lobe, other radio stations using the neighbouring frequency bands (such as the air route surveillance radars) are protected from the interference of the WPRs. This permits the use of WPRs even in urban areas.

### 4.3.6 Wind profiler networks

In addition to the numerous individual profilers constructed around the world, primarily on an experimental basis, there have been built several complete profiler networks characterized by data sharing mechanisms. Among them are:

– The U.S. network was the first constructed and is described in § 4.2.4. It is being expanded and moved to 449 MHz.

– The Japanese network on 1 357.5 MHz is described in § 4.2.5.

– Australia operates four wind profilers in the range 45-56 MHz, with 54-56 MHz being preferred for new installations. Four profilers are operating in the vicinity of 920 MHz and two in the band 1 270-1 295 MHz, with the latter preferred for new installations. The number of systems is expected to grow slowly over the next five years.

– In Europe, several administrations operate profilers in various bands with provisions for continuous data sharing, including:
  – Austria: 1 290 MHz (3)
  – France: 45 MHz (1), 52.05 MHz (1), 1 290 MHz (1)
  – Germany: 482 MHz (1), 1 290 MHz (2)
  – Netherlands: 1 290 MHz (1)
  – Sweden: 52 MHz (1)
  – Switzerland: 1 290 MHz (1)
  – UK: 6.5 MHz (1), 915 MHz (2), 1 290 MHz (2).

In addition, several administrations operate profilers during specific test periods that provide data to the network when operational.

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# CHAPTER 5

## EESS SYSTEMS FOR METEOROLOGICAL ACTIVITIES

# 5 Introduction

The existence of meteorological satellites is well known in most of the world and images produced by them are shown regularly on television and in the popular press. The public is therefore used to seeing colour-augmented, map-registered photographs showing cloud cover, surface temperatures, snow cover and other weather phenomena. Less frequently seen but still of wide (if occasional) interest in much of the world are satellite 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. These have in common the fact that they are recorded primarily using sensors in the visible and infrared regions that many non-scientists consider "light" and not "radio". It therefore surprises some that actual radio frequencies, from VHF through microwaves and into the upper regions of the allocated spectrum, are needed and used by the remote sensing satellite community. There are two classes of remote sensing widely employed: passive and active.

**Passive sensing** involves the use of pure receivers, with no transmitters involved. The radiation sought by these receivers occurs naturally. 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 variety of environmental information can be sensed in this manner. Signal strength on a given frequency may depend on several variables, making the 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 Earth surface.

**Active sensing**, on the other hand, involves both transmitters and receivers aboard a satellite. The uses of active sensing vary from measuring the characteristics of the sea surface to 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 and other RF transmitting stations, either on the ground or in space. The resolution of these problems involves well-known techniques, typically involving coordination with other users on the basis of power limitations, antenna characteristics, time and frequency sharing. A form of vulnerability peculiar to receiving satellites, and particularly those having a large footprint, derives from the fact that they are subjected to accumulated radiation from a multitude of emitters on the ground. Thus, even if a single terrestrial emitter does not radiate enough power to cause harm, a large number of them can still be harmful. This fact is the basis for current concerns regarding high density fixed service (HDFS) emissions. It is the spatial density of HDFS emitters rather than their characteristics which creates a problem.

In the case of passive sensing, the problems are isolated to one direction: the satellite is incapable of causing interference because it does not transmit. Its vulnerability to received interference is unique and is caused by the non-deterministic nature of the signal it is designed to receive. 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 studies dealing with error detection and correction.

Unfortunately, everything known about error correction is of no use when the characteristics of the various received signals are unknown, and this is precisely the case with passive sensing. The very real threat with this type of system is that interference will go undetected, that bad data will be mistaken for good and the conclusions derived from the analysis of these bad data will be seriously flawed. In the case of meteorological applications, lives depend on the validity of these conclusions. Since received data errors can be neither detected nor corrected in passive sensing systems, the maintenance of data integrity depends on the prevention of interference. The imposition of strict limitations on interference is the only solution, with appropriate values for the limits currently under discussion.

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 35 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.

## 5.1 Passive microwave radiometry sensing

### 5.1.1 General capabilities

Passive microwave radiometry is a tool of fundamental importance for the EESS. The EESS operates passive sensors 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 extension 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 radiatively and chemically important trace gases (for instance ozone).

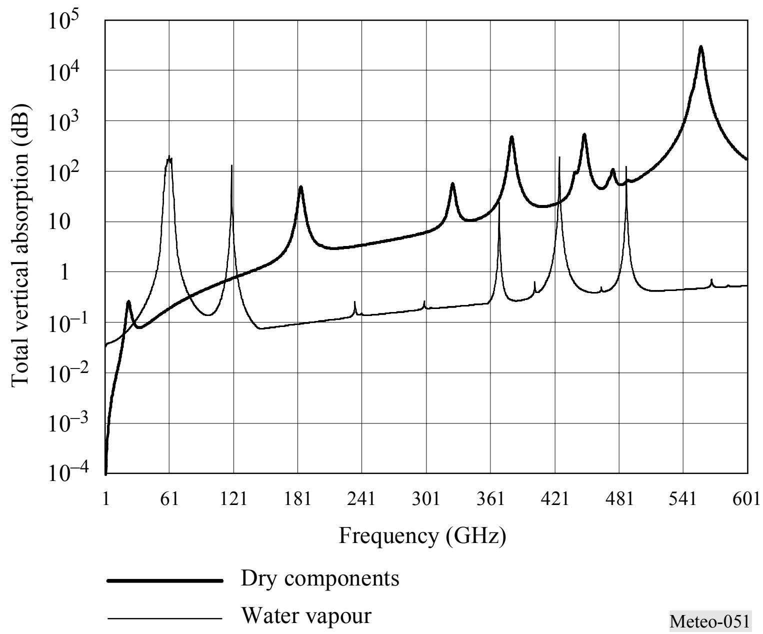
Microwave techniques render possible observation of the Earth's surface and its atmosphere from space orbit even in the presence of clouds, which are almost transparent at frequencies below 100 GHz. This all-weather capability has considerable interest for the EESS because more than 60% of the Earth's surface is overcast with clouds. 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.

### 5.1.2 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

**Zenithal opacity of the atmosphere due to water vapour and dry components**




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, bandwidths, and allocated bandwidths are listed in Table 5-1. Most frequency allocations above 100 GHz contain absorption lines of important atmospheric trace species.

Table 5-2 shows the spectrum occupancy, up to 200 GHz, of major existing nadir-looking passive microwave sensors. Note that in accordance with the revision of the RR Table of Frequency Allocations, a few frequencies currently used by some existing sensors will be abandoned after termination of their operational lifetime.

TABLE 5-1

**Frequency bands and bandwidths used for satellite passive sensing***

| Frequency (GHz) | Necessary or allocated bandwidth (MHz) | Main measurements |
|---|---|---|
| 1.4-1.427 | 100 (27) | Soil moisture, salinity, ocean surface temperature, vegetation index |
| 2.69-2.7 | 60 (10) | Salinity, soil moisture |
| 4.2-4.4 | 200 | Ocean surface temperature |
| 6.7-7.1 | 400 | Ocean surface temperature (no allocation) |
| 10.6-10.7 | 100 | Rain, snow, ice, sea state, ocean wind, ocean surface temperature, soil moisture |
| 15.35-15.4 | 200 | Water vapour, rain |
| 18.6-18.8 | 200 | Rain, sea state, ocean ice, water vapour, snow |
| 21.2-21.4 | 200 | Water vapour, cloud liquid water |
| 22.21-22.5 | 300 | Water vapour, cloud liquid water |
| 23.6-24 | 400 | Water vapour, cloud liquid water |
| 31.3-31.8 | 500 | Window channel associated to temperature measurements |
| 36-37 | 1 000 | Rain, snow, ocean ice, water vapour, cloud liquid water, ocean wind, soil moisture |
| 50.2-50.4 | 200 | $O_2$ (temperature profiling) |
| 52.6-59.3 | 6 700(1) | $O_2$ (temperature profiling) |
| 86-92 | 6 000 | Clouds, ice, snow, rain |
| 100-102 | 2 000 | $N_2O$ |
| 109.5-111.8 | 2 300 | $O_3$ |
| 114.25-122.25 | 8 000(1) | $O_2$ (temperature profiling), CO |
| 148.5-151.5 | 3 000 | Window channel |
| 155.5-158.5 | 3 000 | Window channel (allocation will be terminated on 1 January 2018 based upon RR No. 5.562F) |
| 164-167 | 3 000 | Window channel |
| 174.8-191.8 | 17 000(1) | $H_2O$ (Moisture profiling), $N_2O$, $O_3$ |
| 200-209 | 9 000(2) | $H_2O$, $O_3$, $N_2O$ |
| 226-232 | 6 000(2) | Clouds, CO |
| 235-238 | 3 000(2) | $O_3$ |
| 250-252 | 2 000(2) | $N_2O$ |
| 275-277(3) | 2 000(2) | $N_2O$ |
| 294-306(3) | 12 000(2) | $N_2O$, $O_3$, $O_2$, $HNO_3$, HOCl |
| 316-334(3) | 10 000(2) | Water vapour profiling, $O_3$, HOCl |
| 342-349(3) | 7 000(2) | CO, $HNO_3$, $CH_3Cl$, $O_3$, $O_2$, HOCl, $H_2O$ |

TABLE 5-1 (*end*)

| Frequency (GHz) | Necessary or allocated bandwidth (MHz) | Main measurements |
|---|---|---|
| 363-365(3) | 2 000(2) | $O_3$ |
| 371-389(3) | 18 000(2) | Water vapour profiling |
| 416-434(3) | 18 000(2) | Temperature profiling |
| 442-444(3) | 2 000(2) | Water vapour |
| 486-506(3) | 9 000(2) | $O_3$, $CH_3Cl$, $N_2O$, BrO, ClO |
| 546-568(3) | 22 000(2) | Temperature profiling |
| 624-629(3) | 5 000(2) | Bro, $O_3$, HCl, $SO_2$, $H_2O_2$, HOCl, $HNO_3$ |
| 634-654(3) | 20 000(2) | $CH_3Cl$, HOCl, ClO, $H_2O$, $N_2O$, BrO, $O_3$, $HO_2$, $HNO_3$ |
| 659-661(3) | 2 000(2) | BrO |
| 684-692(3) | 8 000(2) | ClO, CO, $CH_3Cl$ |
| 730-732(3) | 2 000(2) | $O_2$, $HNO_3$ |
| 851-853(3) | 2 000(2) | NO |
| 951-956(3) | 5 000(2) | $O_2$, NO, $H_2O$ |

* For updates to this Table refer to Recommendation ITU-R SA.515.

(1) This bandwidth is occupied by multiple channels.

(2) This bandwidth is occupied by multiple sensors.

(3) RR No. 5.565.

### 5.1.3 Performance parameters

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

#### 5.1.3.1 Radiometric sensitivity

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

$$\Delta T_e = \frac{\alpha T_s}{\sqrt{B\tau}} \quad \text{K} \qquad (5\text{-}1)$$

where:

$B$: receiver bandwidth (Hz)

$\tau$ : integration time (s)

$\alpha$ : receiver system constant (depends on the configuration)

$T_s$: receiver system noise temperature (K).

TABLE 5-2

## Centre frequencies or number of channels of major existing microwave passive sensors

| Name | Portos | IRIS | MIRAS | MIMR | AMSR | AMSR-E | SMMR | SSM/I | SSM/T | SSMI/S | TMI | MIVZA | MZOAS | MTVZA | MHS | AMSU-A/B | MWRS | MWRI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Mission** | **Airborne** | **Airborne** | **Airborne** | **METOP** | **ADEOS** | **Aqua** | **NIMBUS** | **DMSP** | **DMSP** | **DMSP** | **TRMM** | **Meteor** | **Meteor** | **Meteor** | **NOAA /** | **METOP** | **FY-3** | |
| **Antenna (cm)** | | | | **150** | **200** | **160** | **80** | **65** | **60** | **65** | **65** | **40** | **80** | **20** | **20** | **20** | | |
| **Scanning** | NA | Interf. | Interf. | Conical | Conical | Conical | Conical | Conical | Cross-tr. | Conical | Conical | Conical | Conical | Conical | Cross-tr. | Cross-tr. | | |
| **Freq. (GHz)** | Centre frequencies (A number of channels have two polarizations, and the channels indicated by a symbol * have the vertical polarization only) | | | | | | | | | | | | | | | | | |
| 1.37-1.4: | - | - | - | - | - | | - | - | - | - | - | - | - | - | | - | | |
| 1.4-1.427: | 1.41 | - | 1.40 | - | - | | - | - | - | - | - | - | - | - | | - | | |
| 2.69-2.7: | - | - | - | - | - | | - | - | - | - | - | - | - | - | | - | | |
| 4.2-4.4: | - | - | - | - | - | | - | - | - | - | - | - | - | - | | - | | |
| 4.99-5.0: | 5.05 | - | - | - | - | | - | - | - | - | - | - | - | - | | - | | |
| 6.425-7.25: | - | 6.50 | - | 6.80 | 6.93 | 6.925 | 6.60 | - | - | - | - | - | 6.20 | - | | - | | |
| 10.6-10.68: | 10.65 | - | - | 10.65 | 10.65 | 10.65 | - | - | - | - | 10.65 | - | - | - | | - | | |
| 10.68-10.7: | - | - | - | - | - | | 10.69 | - | - | - | - | - | 10.80 | - | | - | 10.65 | |
| 15.2-15.35: | - | - | - | - | - | | - | - | - | - | - | - | - | - | | - | | |
| 15.35-15.4: | - | - | - | - | - | | - | - | - | - | - | - | - | - | | - | | |
| 18.6-18.8: | - | - | - | 18.70 | 18.70 | 18.70 | 18.00 | 19.35 | - | 19.35 | 19.35 | - | - | - | | - | 18.70 | |
| 21.2-21.4: | - | - | - | - | - | | 21.00 | - | - | - | 21.30 | 20.00 | 20.00 | - | | - | | |
| 22.21-22.5: | - | - | - | - | - | | - | 22.24 | - | 22.24 | - | - | 22.20 | - | | - | | |
| 23.6-24.0: | 23.80 | - | - | 23.80 | 23.80 | 23.80 | - | - | - | - | - | - | - | - | | 23.80 | 23.80 | 23.9 |
| 31.3-31.5: | - | - | - | - | - | | - | - | - | - | - | - | - | - | | 31.4 | | 31.40 |
| 31.5-31.8: | - | - | - | - | - | | - | - | - | - | - | - | - | - | | - | | |
| 36.0-37.0: | 36.50 | - | - | 36.50 | 36.50 | 36.50 | 37.00 | 37.00 | - | 37.00 | 37.00 | 35.00 | 35.00 | - | | - | 36.50 | |
| 50.2-50.4: | - | - | - | - | 50.30 * | | - | - | 50.50 | 50.30 | - | - | - | - | | 50.30 | | 50.31 |
| 51.4-54.25: | - | - | - | - | 52.80 * | | - | - | 53.20 | 2 ch. | - | - | - | 3 ch.& sub | | 3 ch.& sub | | 53.74 |
| 54.25-58.2: | - | - | - | - | - | | - | - | 2 ch. | 3 ch.& sub | - | - | - | 12 ch.& sub | | 22 ch.& sub | | 54.96& 57.95 |
| 58.2-59.0: | - | - | - | - | - | | - | - | 2 ch. | - | - | - | - | - | | - | | |
| 59.0-64.0: | - | - | - | - | - | | - | - | 59.40 | 21 ch.& sub | - | - | - | - | | 12 ch.& sub | | |
| 64.0-65.0: | - | - | - | - | - | | - | - | - | - | - | - | - | - | | - | | |
| 86.0-92.0: | 90.00 | - | - | 89.00 | 89.00 | 89.00 | - | 85.50 | 90.00 | 91.66 | 85.50 | 94.00 | 94.00 | - | 89 | 89.00 | 89.00 | 89.00 |
| 100-102: | - | - | - | - | - | | - | - | - | - | - | - | - | - | | - | | |
| 105-116: | - | - | - | - | - | | - | - | - | - | - | - | - | - | | - | | |
| 116-126: | - | - | - | - | - | | - | - | - | - | - | - | - | - | | - | | |
| 150-151: | - | - | - | - | - | | - | - | 150.00 | 150.00 | - | - | - | - | | 150.00 | 150.00 | |
| 156-158: | - | - | - | - | - | | - | - | - | - | - | - | - | - | 157 | - | | |
| 164-168: | - | - | - | - | - | | - | - | - | - | - | - | - | - | | - | | |
| 174.8-194.8: | - | - | - | - | - | | - | - | 6 ch.& sub | 6 ch.& sub | - | - | - | - | 6 ch.& sub | 6 ch.& sub | | |

#### 5.1.3.2 Radiometer threshold $\Delta P$

This is the smallest power change that the passive sensor is able to detect. $\Delta P$ is given by:

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

where:

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

$\Delta P$ above is computed using $\Delta T_e$. In the future, $T_s$ will decrease as well as $\Delta T_e$ (see equation (5-1)). Therefore $\Delta P$ must be computed using a reasonable foreseen $\Delta T_e$ rather than the $\Delta T_e$ of current technology. In the same manner, $\tau$ will increase (pushbroom concept). $\tau$ must also be chosen based on reasonable future expectations.

#### 5.1.3.3 Geometric resolution

In the case of two-dimensional measurements of surface parameters (see § 5.1.4), 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 (see § 5.1.5), 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.

#### 5.1.3.4 Integration time

The integration time is also an important parameter, 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.

### 5.1.4 Typical operating conditions of passive sensors

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

#### 5.1.4.1 Low Earth orbiting satellites

Systems based on satellites in low sun-synchronous polar orbit are used to acquire high-resolution environmental data on a global scale. The orbital mechanic limits the repeat rate of measurements. A maximum of two global coverage's at 12 h intervals are obtained daily, with one 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, and may change in the future.

#### 5.1.4.2 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 every 30 min or less.

### 5.1.5 Observation of Earth's surface features

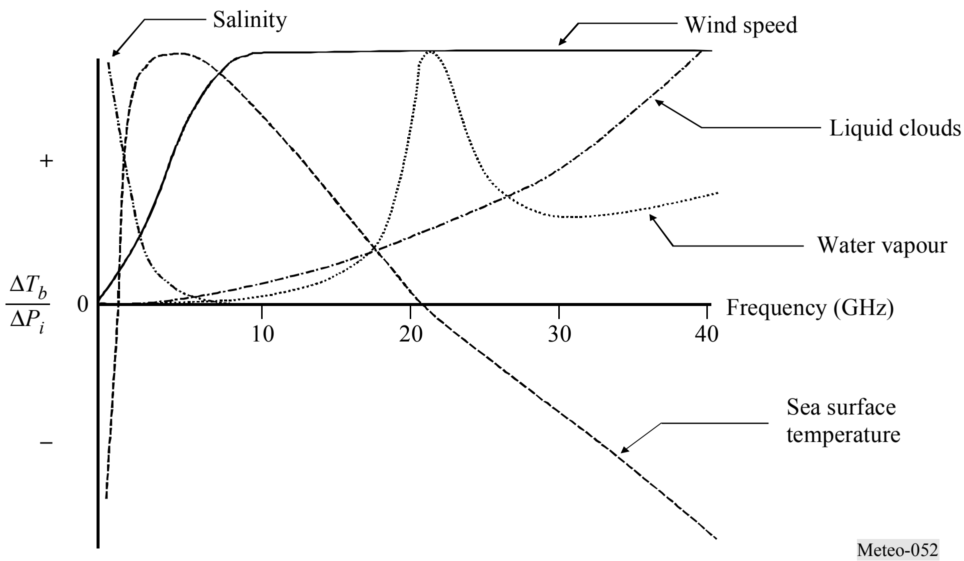
For the measurement of surface parameters, the radiometric "window" channels must be selected such that a regular sampling over the microwave spectrum from 1 GHz to 90 GHz is achieved (one frequency/octave, on average). However, highly accurate settings of frequencies, in general, are not required because 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 the Figs. 5-2 to 5-4, which represent the sensitivity of natural microwave emissions to various geophysical parameters depending on frequency.

### 5.1.5.1 Over ocean surfaces

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

FIGURE 5-2

**Sensitivity of brightness temperature to geophysical parameters over ocean surface**




– 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 23 GHz, while liquid clouds are obtained via measurements around 36 GHz; and

– five frequencies (around 6 GHz, 10 GHz, 18 GHz, 23 GHz and 36 GHz) are necessary for determining the dominant parameters.

### 5.1.5.2 Over land surfaces

Over land surfaces, the problem 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 radiometer has been through a number of different media: basically the soil, perhaps snow and/or ice, the vegetation layer, atmosphere and clouds, and occasionally rain. 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, 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. The way 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

**Sensitivity of brightness temperature to geophysical parameters over land surfaces**

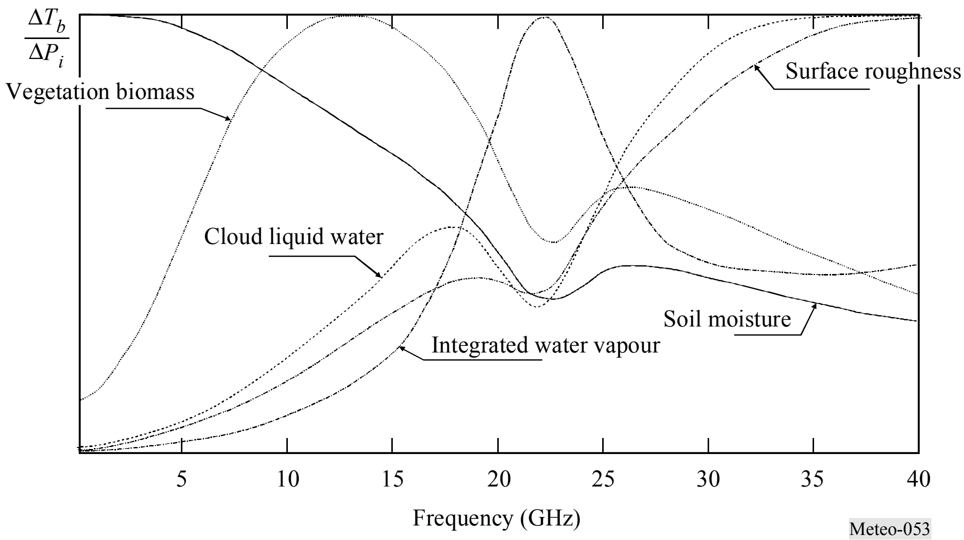



Figure 5-3 shows that over land and for an average temperate area, it is necessary to have access to:

– 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 19 GHz channel when the surface and atmospheric contributions can be estimated.

Snow covered areas are important to monitor and here again the necessity for 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.

#### 5.1.5.3 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. In order to remove refraction affects due to atmosphere, the utilization of highly accurate altimetric data require that they be complemented with a set of auxiliary passive measurements around 18.7 GHz, 23 GHz and 36 GHz.

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

### 5.1.6 Main technical characteristics

Most passive microwave sensors designed for imaging the Earth's surface features use a conical scan configuration centred around the nadir 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.

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

– useful swath: 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

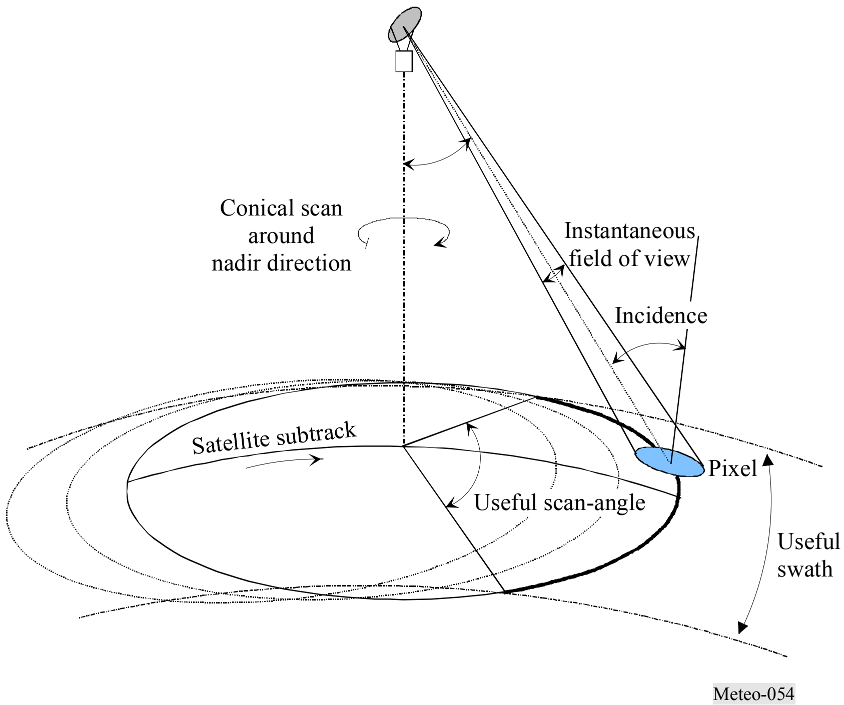
– pixel size varying with frequency and dish size, typically from 50 km at 6.9 GHz to 5 km at 89 GHz in case of the NASDA's AMSR instrument (2 m dish) and

– scanning period and antenna feed arrangement are chosen in order to ensure full coverage and optimum integration time (radiometric resolution) at all 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. These sensors will use fixed arrays of small antennas instead of large scanning antennas.

FIGURE 5-4

**Typical geometry of conically scanned passive microwave radiometers**




### 5.1.7 Performance and interference criteria

Summary of performance and interference criteria for surface measurements based on Recommendations ITU-R SA.1028 – Performance criteria for satellite passive remote sensing and ITU-R.SA. 1029 – Interference criteria for satellite passive remote sensing is presented in Table 5-3.

TABLE 5-3

**Summary of performance and interference criteria for surface measurements**

| Frequency (GHz) | Acceptable interference level (dBW) | Reference bandwidth (MHz) | Required $\Delta T_e$ (K) |
|---|---|---|---|
| Near 1.4 | –171 | 27 | 0.1 |
| Near 2.7 | –174 | 10 | 0.1 |
| Near 4 | –161 | 100 | 0.3 |
| Near 6 | –164 | 100 | 0.3 |
| Near 11 | –163 | 20 | 1.0 |
| Near 15 | –166 | 50 | 0.2 |
| Near 18 | –155 | 100 | 1.0 |
| Near 21 | –163 | 100 | 0.2 |
| 22.235 | –160 | 100 | 0.4 |
| Near 24 | –163 | 100 | 0.2 |
| Near 31 | –163 | 100 | 0.2 |
| Near 37 | –156 | 100 | 1.0 |
| Near 90 | –153 | 200 | 1.0 |

### 5.1.8 Three-dimensional measurement of atmospheric parameters

The electromagnetic spectrum contains many frequency bands where, due to molecular resonance's, absorption mechanisms by certain atmospheric gases are taking place (see Fig. 5-1). Frequencies at which such phenomena occur characterize the gas (for instance $O_2$, $O_3$, $H_2O$, 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 the EESS 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 Kirchoff's law: equation (5-3):

$$l = \alpha \cdot L \tag{5-3}$$

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)

$\alpha$: characterizes the gas ($O_2$, $CO_2$, $H_2O$, $O_3$, etc.).

Two atmospheric gases, $CO_2$ and $O_2$, play a predominant role because their concentration and pressure in the atmosphere (two parameters which determine the absorption ratio $\alpha$), 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 radiatively and chemically important atmospheric gases of variable and unknown concentration ($H_2O$, $O_3$, $CH_4$, ClO, etc) are also collected. But in that case, the knowledge of atmospheric temperature profiles is mandatory in order to retrieve the unknown vertical concentration profiles of these gases.

#### 5.1.8.1 Passive microwave atmospheric vertical sounders

Vertical atmospheric sounders 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. 5-5 to 5-7. Figure 5-5 also shows the position and the status of allocations, which are required by EESS (passive) in the 50-71 GHz band, as they result from sharing studies and from WRC-97. Note the very important variability of the water vapour absorption spectrum around 183 GHz, depending on climatic zone and on local weather conditions.

#### 5.1.8.2 Mechanism of vertical atmospheric sounding

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

FIGURE 5-5

## $O_2$ absorption spectrum along a vertical path around 60 GHz

(multiple absorption lines)

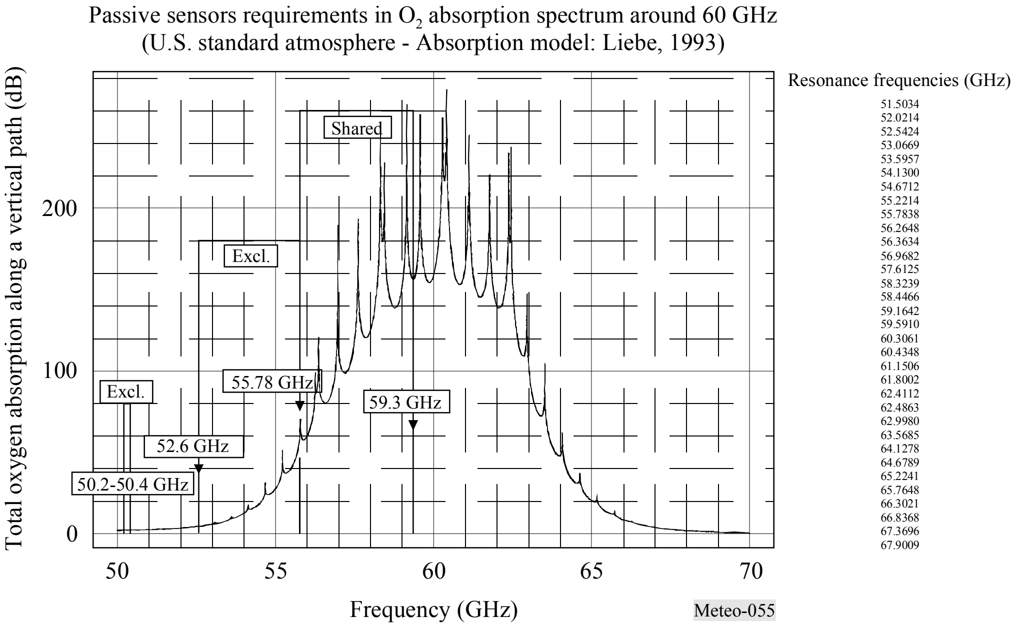



FIGURE 5-6

## $O_2$ absorption spectrum along a vertical path around 118.75 GHz

(one unique absorption line)

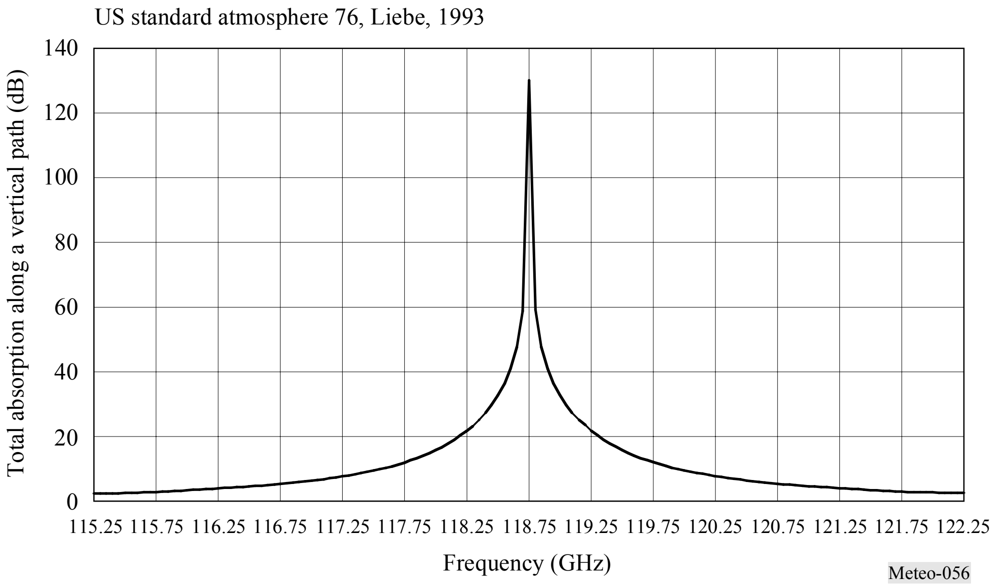
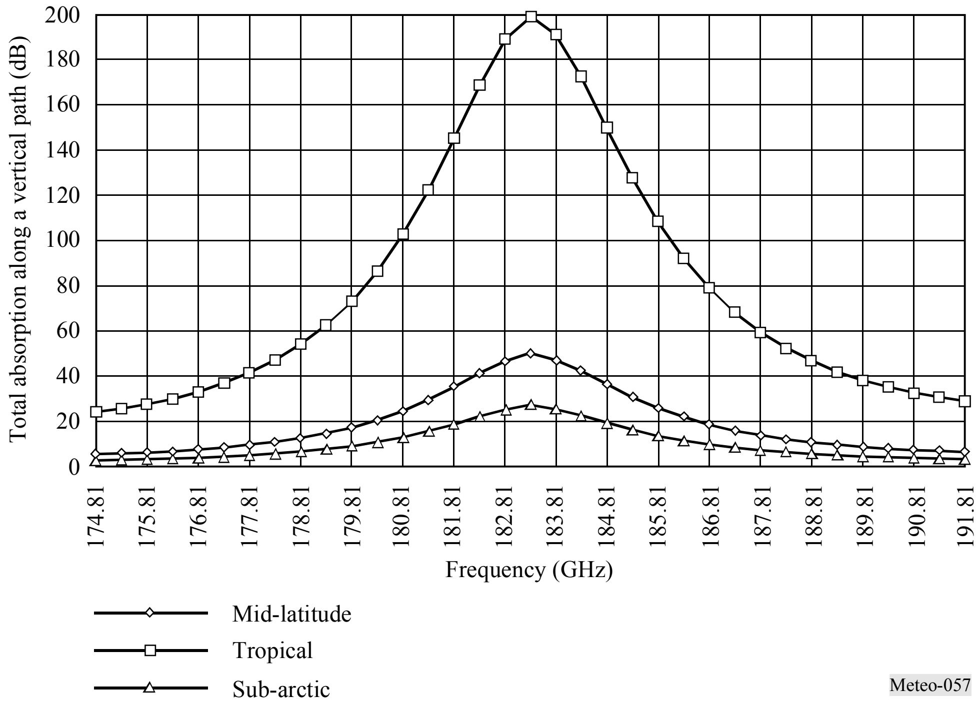


FIGURE 5-7

**Water vapour absorption spectrum along a vertical path around 183.31 GHz**




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 occurs 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. 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. 5-8.

Note the particular importance of Channels 1 (23.8 GHz), 2 (31.5 GHz), and 15 (90 GHz). 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. In Fig. 5-8, it can be seen that:

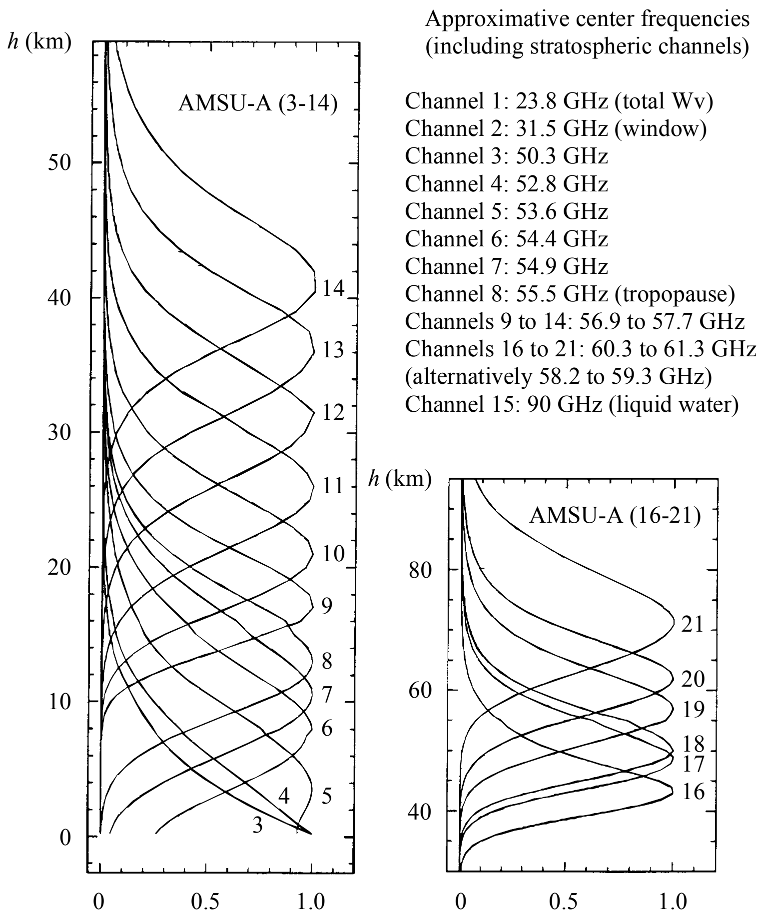
– Channel 1 is close to a $H_2O$ absorption peak. It is used to retrieve the total water vapour content along the line of sight, and to determine the corrections, which are necessary in the other channels.

– 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.

FIGURE 5-8

**Typical weighting functions for a microwave temperature sounder operating near 60 GHz**



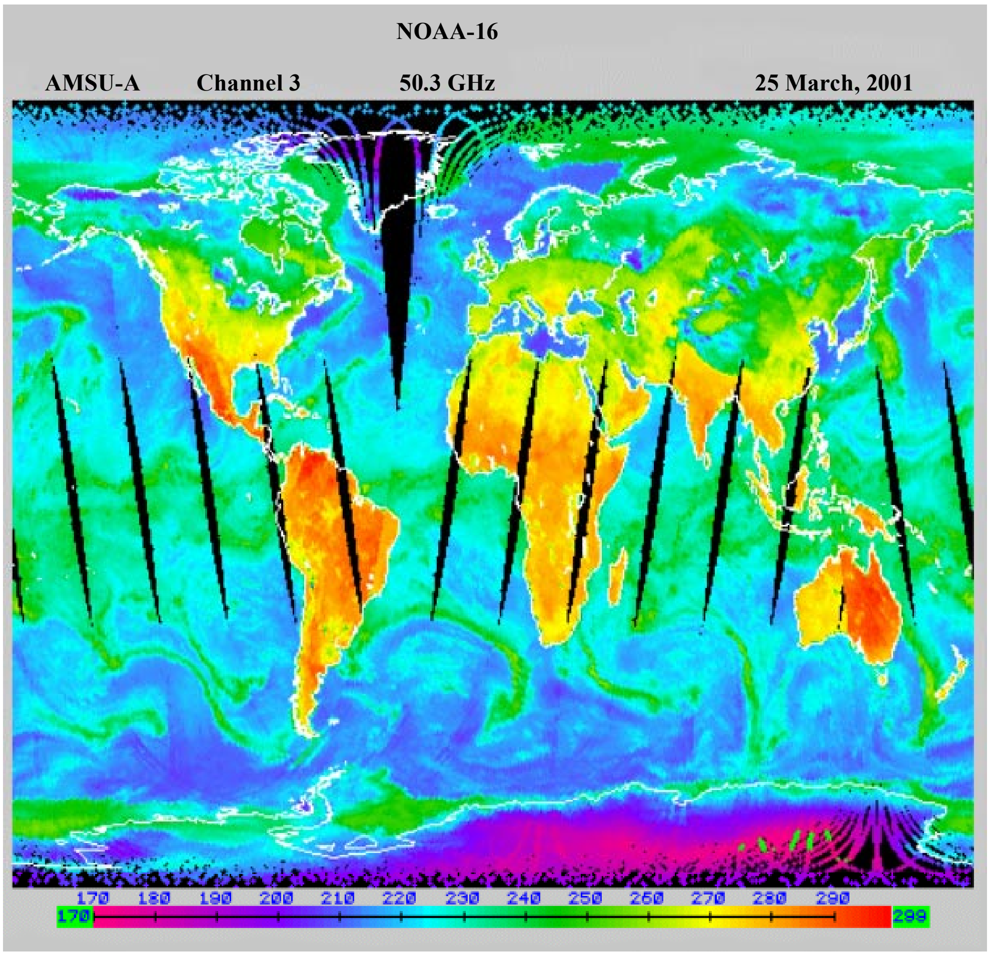

Meteo-058

### 5.1.8.3 Utilization of vertical atmospheric sounding

The vertical temperature and humidity profiles are essentially used to feed the numerical weather prediction (NWP) models, which need to be initialized at least every 6 h. There are global NWP (worldwide) models as in the United Sates of America, Europe, China, Australia, Brazil, etc. to get a 5 to 10 days weather forecast with a geographical resolution of 50 km. Also, in increasing numbers, there are regional/local models for a fine mesh prediction (10 km or less) on a short-range basis (6 h to 48 h). Figure 5-9 shows the global composite of radiance temperature (K) measurements from AMSU-A Channel 3, containing measurements produced in a time window of about 12 h. Channel 3 observations include emission and reflection from the surface plus emission from oxygen mostly in the first 5 km above the surface (see Fig. 5-8).

FIGURE 5-9

**Global composite of radiance temperature (K) measurements from AMSU-A Channel 3**



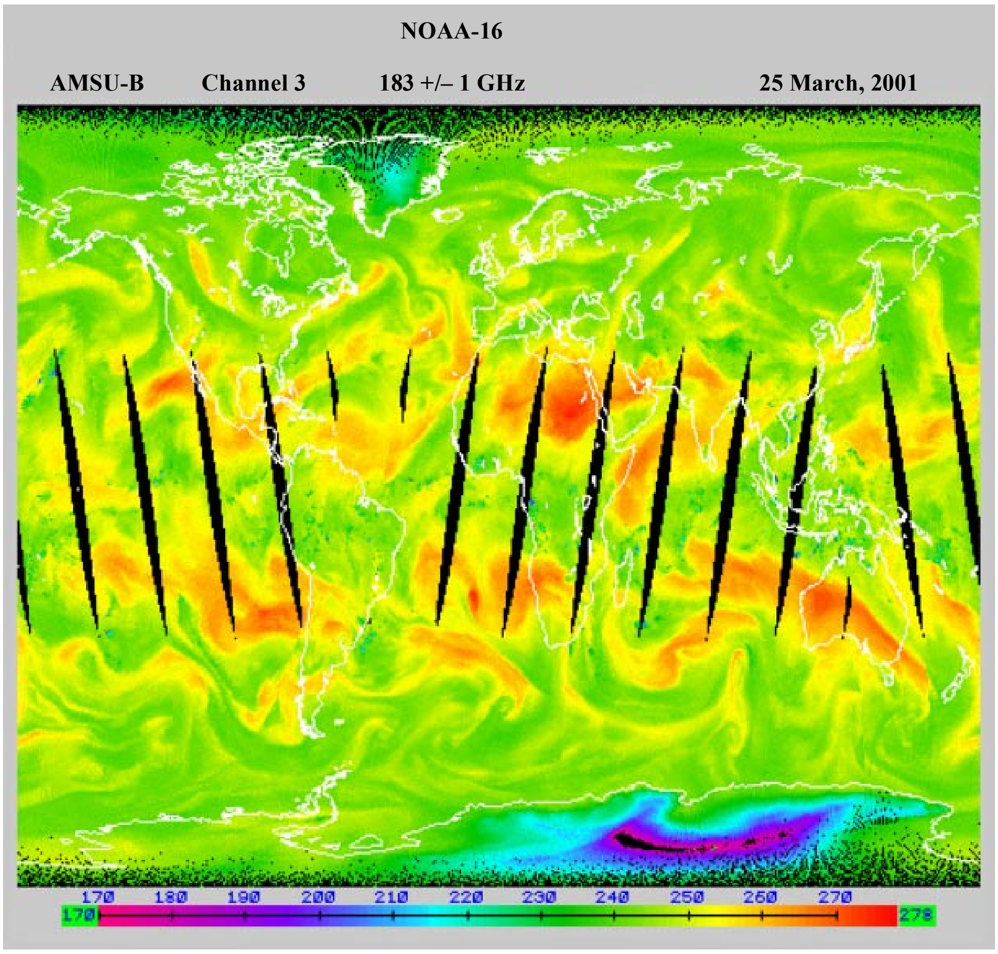

Meteo-059

Figure 5-10 shows the global composite of radiance temperature (K) measurements from AMSU-B Channel 3, containing measurements produced in a time window of about 12 h. AMSU-B is a radiometer operated in partnership 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 5-10

**Global composite of radiance temperature (K) measurements from AMSU-B Channel 3**




Meteo-0510

It is necessary to improve and increase the initialization of the models at least every 6 h on a world-wide 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 every 3 h or less.

#### 5.1.8.4 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 5-4.

TABLE 5-4

**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 |

#### 5.1.8.5 Passive microwave limb sounders

Microwave limb sounders (MLS), 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. 5-11;

– 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;

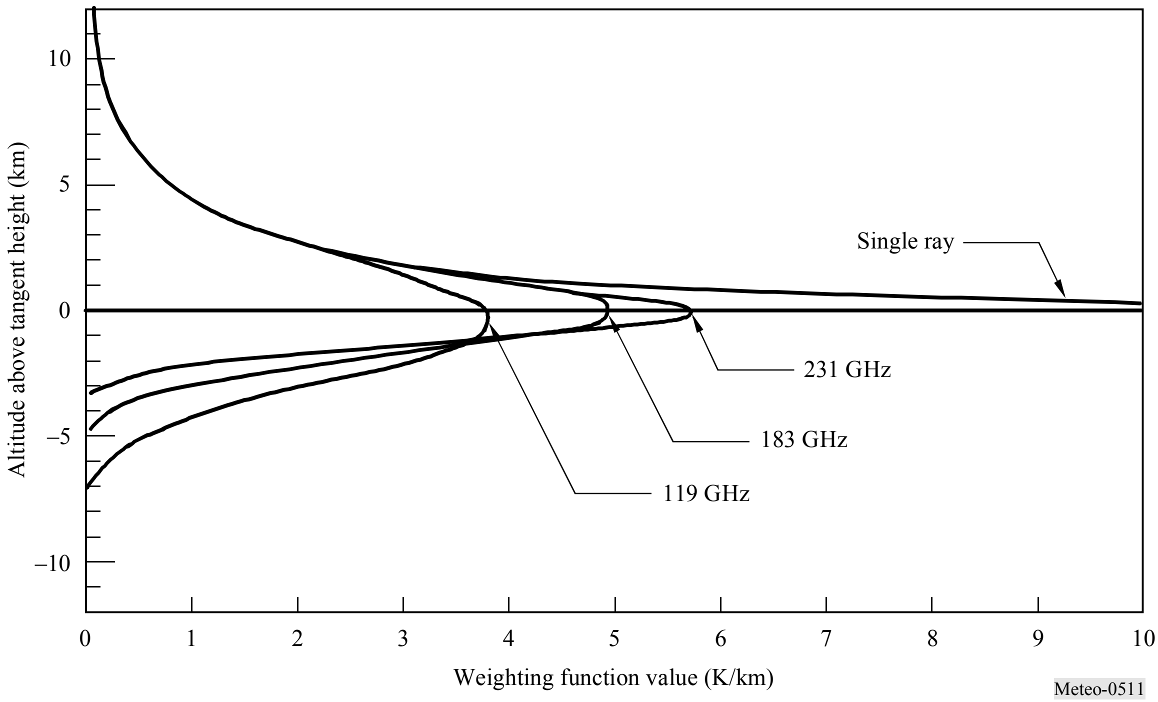
– the horizontal resolution along the line of sight is principally determined by the radiative transfer through the atmosphere;

– the space background is optimum for emission measurements; and

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

FIGURE 5-11

**MLS vertical weighting functions (diffraction limited 1.6 m antenna, 600 km altitude)**




### 5.1.8.5.1 MLS-Upper atmosphere research satellite (UARS)

Microwave limb sounders (MLS-UARS) were first launched in 1991 by NASA/JPL, and perform the following functions:

– scans 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. 5-11;

– 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 5-5).

### 5.1.8.5.2 MLS New Generation (EOS-B)

The new generation of MLS (EOS-B) measures 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.

TABLE 5-5

**Measurement objectives of MLS and spectral regions**

| Geophysical parameter | Spectral region (GHz) | Altitude (km) | RMS noise (interval time) |
|---|---|---|---|
| Atmospheric pressure | 63 | 30-70 | 1% (2 s) |
| Wind velocity | 119 | 70-110 | 2-10 m/s (10 s) |
| Temperature | | 20-100 | 0.5-3 K (2 s) |
| $O_2$ | | 80-120 | $3 \times 10^{-3}$ v/v (2 s) |
| Magnetic field | | 80-110 | 0.3-1 m gauss (10 s) |
| $H_2O$ | 183 | 15-90 | $1 \times 10^{-7}$ v/v (2 s) |
| ClO | 205 | 20-40 | $2 \times 10^{-10}$ v/v (10 s) |
| $O_3$ | | 15-90 | $1 \times 10^{-8}$ v/v (2 s) |
| $H_2O_2$ | | 20-50 | $9 \times 10^{-10}$ v/v (10 s) |
| $O_3$ | 231 | 15-90 | $1 \times 10^{-8}$ v/v (2 s) |
| CO | | 15-100 | $1 \times 10^{-7}$ v/v (10 s) |

MLS observes the details of ozone chemistry by measuring many radicals, reservoirs, and source gases in chemical cycles which 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 UARS previously demonstrated the MLS capability of measuring upper tropospheric water vapor profiles, knowledge of which is essential for understanding climate variability and global warming but which previously has been extremely difficult to observe reliably on a global scale.

EOS-B MLS continues the atmospheric limb sounding effort started on UARS MLS, and uses advanced technology to provide important new measurements.

TABLE 5-6

**MLS (EOS-B) spectral regions and measurement objectives**

| Spectral region (GHz) | Atmospheric species | Required sensitivity 0.6 s integration, SSB (K) |
|---|---|---|
| 642.85 | $CH_3Cl$, ClO, BrO, HCl, HOCl, $SO_2$ | $T_{sys} < 10\,000$ |
| 1 228.95 | HF | $T_{sys} < 15\,000$ |
| 2 522.78 | OH | $T_{sys} < 30\,000$ |

#### 5.1.8.5.3 Sub-millimetre observation of process in the atmosphere noteworthy for ozone

The sub-millimetre observation of process in the atmosphere noteworthy for ozone (SOPRANO) system has been developed by ESA. This system intended to detect species such as $O_3$, ClO, HCl, NO, $O_2$, BrO, HOCl, $CH_3Cl$, $N_2O$, $HNO_3$, etc. Observations are made typically in the 10-50 km altitude range. Antenna gain is around 70 dBi. The SOPRANO channels and radiometric objectives are shown in Table 5-7.

TABLE 5-7

**SOPRANO channels and radiometric objectives**

| Millimetre-wave channels (GHz) | Atmospheric species | System noise temperature (SSB, K) | NET (0.3 s interval, 3 MHz resolution) (K) |
|---|---|---|---|
| 497-506 | BrO, $O_3$, ClO, $CH_3Cl$, $N_2O$ | 3 800 | 2.5 |
| 624.6-629 | HCl, HOCl | 7 900 | 8 |
| 952-955 | $O_2$, NO | 7 600 | 8 |

#### 5.1.8.5.4 Millimetre-wave acquisitions for stratosphere-troposphere exchanges research

The millimetre-wave acquisitions for stratosphere-troposphere exchanges research (MASTER) system has also been developed by ESA.

Instrument envisioned for the atmospheric chemistry explorer (ACE) satellite, in low-Earth, Sun-synchronous orbit. It is intended to detect CO, $O_3$, $H_2O$, $O_2$, $SO_2$, $N_2O$, $HNO_3$, ClO, BrO, $CH_3Cl$, etc. Observations are made typically in the 0-50 km altitude range. Antenna gain is around 70 dBi. Table 5-8 contains MASTER channels and radiometric objectives.

TABLE 5-8

**MASTER channels and radiometric objectives**

| Millimetre-wave channels (GHz) | Atmospheric species | System noise temperature (SSB (K)) | NET (0.3 s interval, 50 MHz resolution) (K) |
|---|---|---|---|
| 199-207 | $O_3$, $N_2O$, $H_2O$ | 3 500 | 1 |
| 296-306 | $O_3$, $N_2O$, $O_2$, $HNO_3$ | 5 200 | 1.5 |
| 318-326 | $O_3$, $H_2O$, $HNO_3$ | 5 200 | 1.5 |
| 342-348 | $O_3$, CO, $HNO_3$ | 5 200 | 1.5 |
| 498-505 | $O_3$, $N_2O$, $CH_3Cl$, BrO, ClO | 5 200 | 1.5 |

#### 5.1.8.5.5 Superconducting submillimeter-wave limb-emission sounder

The superconducting submillimeter-wave limb-emission sounder (SMILES) instrument is developed by NASDA/CRL. Table 5-9 contains SMILES spectral regions and measurement objectives.

TABLE 5-9

**SMILES spectral regions and measurement objectives**

| Spectral region (GHz) | Atmospheric species | System noise temperature (SSB (K)) |
|---|---|---|
| 624-629<br>649-653 | $O_3$, HCl, $SO_2$, $H_2O_2$, $HO_2$,<br>HOCl, $HNO_3$, ClO, BrO | $T_{sys} < 500$ |

The SMILES instrument scans the antenna to achieve an altitude resolution of about 3.5 km at tangential altitude ranging from upper troposphere (10 km) to lower mesosphere (60 km) from the orbit of the international space station (ISS). SMILES adopts an ultra-low noise receiver with superconductor-insulator-superconductor (SIS) mixers. The SMILES instrument is to be launched in 2005.

#### 5.1.8.5.6 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 kinds of signals because the atmosphere is a highly unstable medium with fast changing characteristics, spatially and temporally. They are therefore extremely vulnerable to interference, which may have very serious detrimental consequences:

– It was demonstrated that as few as 0.1% of contaminated satellite data 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 may render impossible the recognition of new developing weather systems, and vital indications of rapidly developing potentially dangerous storms may be missed; and

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

Recommendations ITU-R SA.1028 and ITU-R SA.1029 set the required radiometric performances and the permissible interference level as follows:

– *In the 50 to 66 GHz frequency band:* The required radiometric resolutions are 0.3 K for scanning sensors and 0.1 K for push-broom sensors. The resulting interference thresholds are –161 dBW for a scanning sensor and –166 dBW for a push broom sensor, in a reference bandwidth of 100 MHz. These levels are equivalent to brightness temperatures increase of 0.06 K and 0.02 K respectively, and can be considered as a normal contribution to the error budget of the instrument.

– *Above 100 GHz:* The required radiometric resolution is currently 0.2 K at all frequencies, leading to an interference threshold of –160 dBW, in a reference bandwidth of 200 MHz. However, these figures need to be revised in light of the most recent achievements in atmospheric sciences.

Recommendation ITU-R SA.1029 states that "the interference levels given above can be exceeded for less than 0.01% of the time in the sensor's service area for three dimensional measurements of atmospheric temperature or gas concentration in the absorption bands including those in the range 50.2-61.3 GHz and bands near 118 GHz and 183 GHz".

## 5.2 Active sensors

### 5.2.1 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.

*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.

*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 5-10.

TABLE 5-10

**Active spaceborne sensor characteristics**

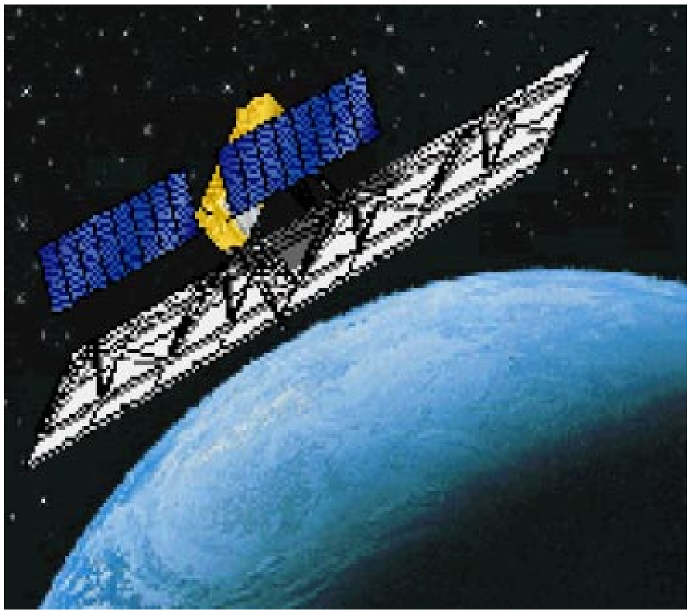
| Characteristic | Sensor types | | | | |
|---|---|---|---|---|---|
| | **SAR** | **Altimeter** | **Scatterometer** | **Precipitation radars** | **Cloud profile radars** |
| Viewing geometry | Side-looking at 10°-55° off nadir | Nadir-looking | – Six fan beams in azimuth<br>– Two conically scanning beams | Nadir-looking | Nadir-looking |
| Footprint/-dynamics | – Fixed to one side<br>– ScanSAR | Fixed at nadir | – Fixed in azimuth<br>– Scanning | Scanning across nadir track | Fixed at nadir |
| Antenna beam | Fan beam | Pencil beam | – Fan beams<br>– 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 | Short pulses | Short pulses |
| Bandwidth | 20-300 MHz | 320 MHz | 5-80 kHz | 14 MHz | 300 kHz |
| Duty factor (%) | 1-5 | 46 | 31 | 0.9 | 1-14 |
| Service area | Land/coastal/ocean | Ocean/ice | Ocean/ice/land | Land/ocean | Land/ocean |

### 5.2.2 Synthetic aperture radars

SARS provide radar images of the Earth's surface. Figure 5-12 shows an artist's rendition of a proposed LightSAR L-band system. 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 $c/2/(\mathrm{BW}\ \sin\ \theta)$, where $c$ is the velocity of light, BW is the RF bandwidth, and $\theta$ 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. The allowable image pixel quality degradation determines the allowable interference level. Figure 5-14 shows a SAR image taken by SIR-C of the Dead Sea between Israel and Jordan.

FIGURE 5-12

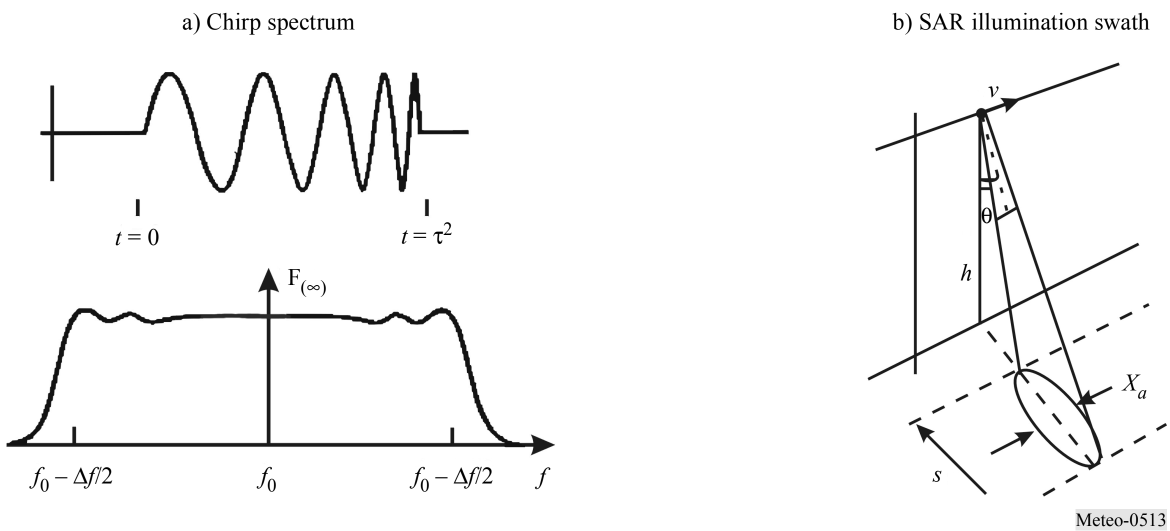
**LightSAR L-band SAR**



Meteo-0512

FIGURE 5-13

**Chirp spectrum and SAR illumination swath**




Meteo-0513

FIGURE 5-14

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

Meteo-0514

### 5.2.3 Altimeters

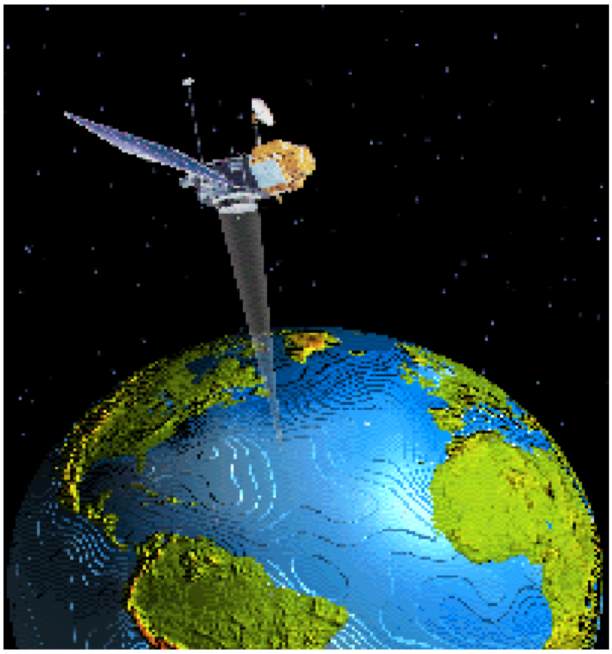
Altimeters provide the altitude of the Earth's ocean surface. Figures 5-15, 5-16a) and 5-16b) are an illustration of the TOPEX altimeter and its accuracy. The choice of RF centre frequency depends on the ocean surface interaction with the EM field. Dual frequency operation allows ionospheric delay compensation. For instance, TOPEX/POSEIDON uses frequencies around 13.6 GHz and 5.3 GHz. The wide RF bandwidth affects the height measurement accuracy. The time difference accuracy $\Delta t$ is inversely proportional BW, where BW is the RF bandwidth. The allowable height accuracy degradation determines the allowable interference level.

### 5.2.4 Scatterometers

Scatterometers provide the wind direction and speed over the Earth's ocean surface. The choice of RF centre frequency depends on the ocean surface interaction with the EM field and its variation over aspect angle. Figure 5-18 shows the variation of backscatter level with aspect angle relative to the wind velocity vector direction.

FIGURE 5-15

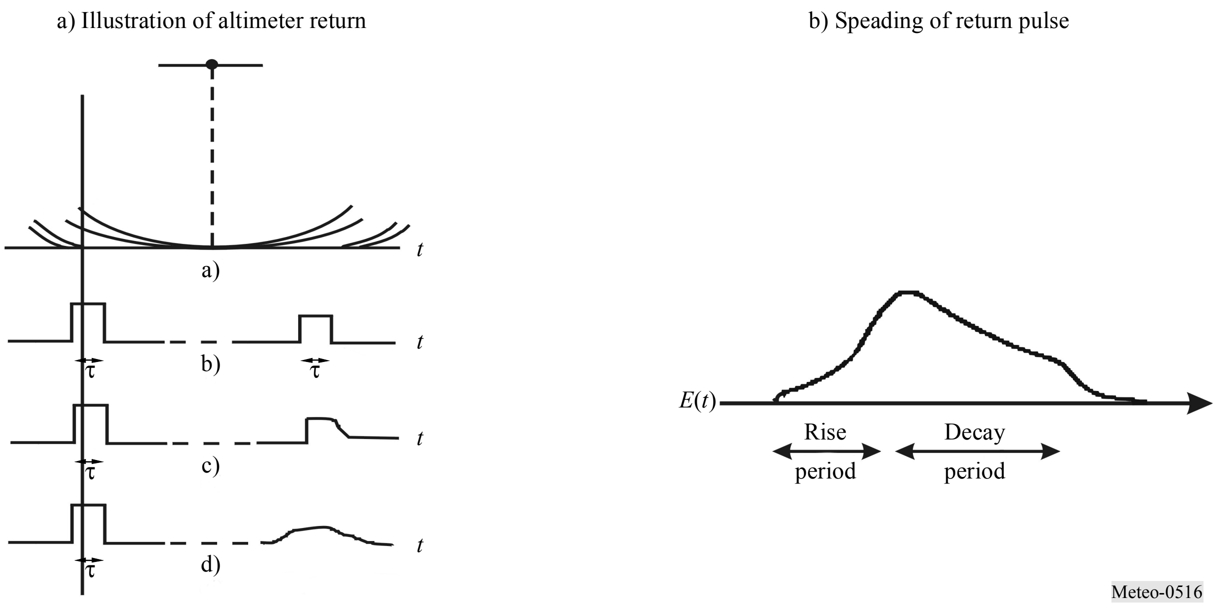
**TOPEX satellite**



Meteo-0515

FIGURE 5-16

**Illustration of altimeter return and spreading of return pulse**




Meteo-0516

FIGURE 5-17

**TOPEX/POSEIDON detection of warm sea temperatures of El Niño in Pacific Ocean**

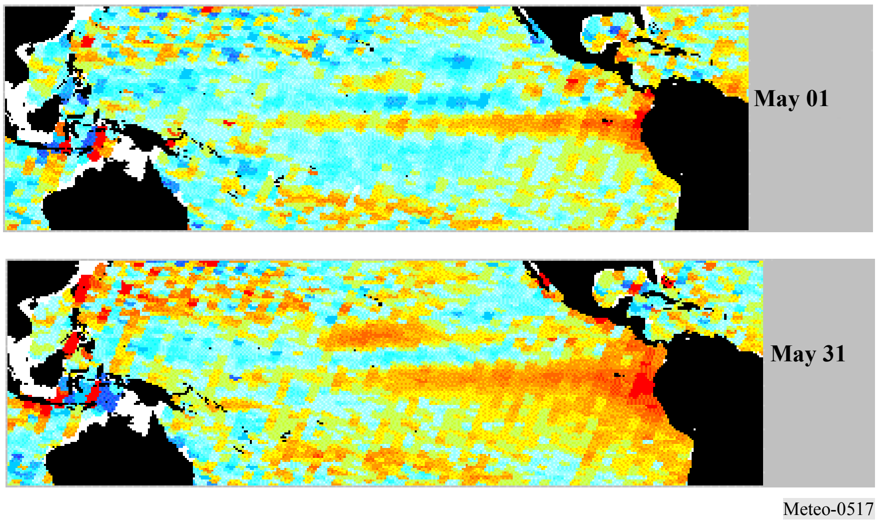
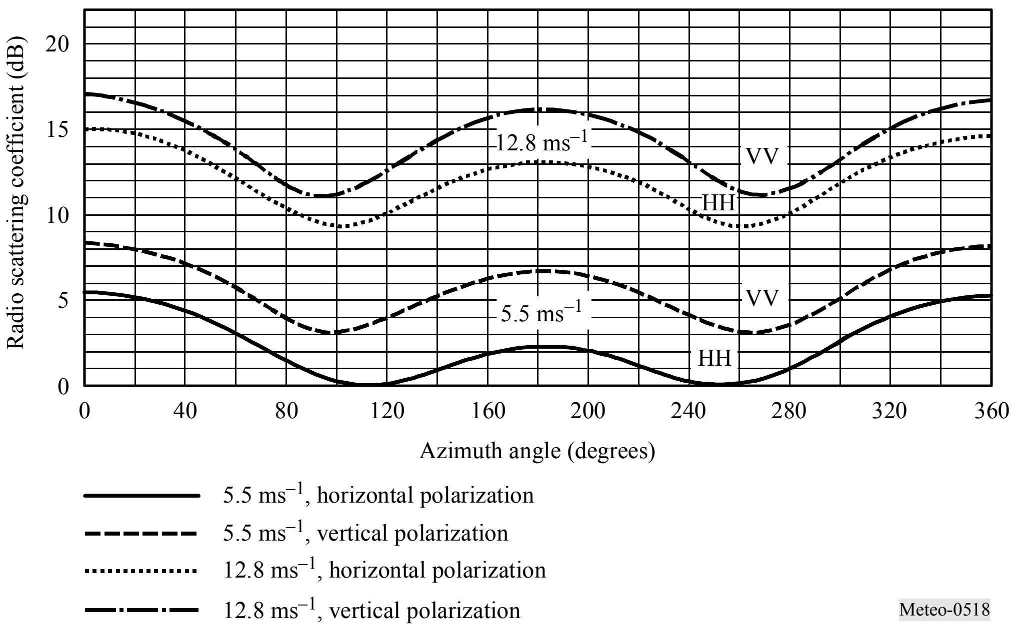



FIGURE 5-18

**Variation of backscatter with aspect angle**




As shown in Fig. 5-19, SCAT illuminates the Earth's surface at several different fixed aspect angles. In Fig. 5-20 the SEAWINDS scanning pencil beam illuminates scans at two different look angles from nadir, and scans 360° about nadir in azimuth. The narrow RF signal bandwidth provides the needed measurement cell resolution. For NSCAT, only 2-15 kHz is needed for the 25 km resolution. The allowable wind speed accuracy degradation determines the allowable interference level.

FIGURE 5-19

**NSCAT fixed footprint**

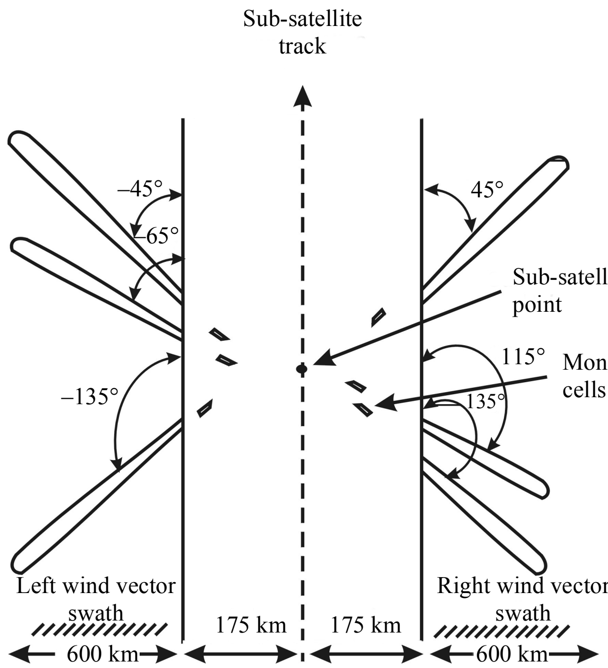



FIGURE 5-20

**Seawinds pencil beam scan**

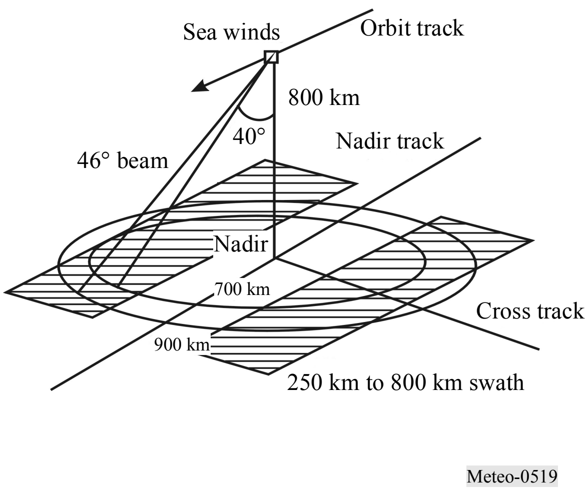
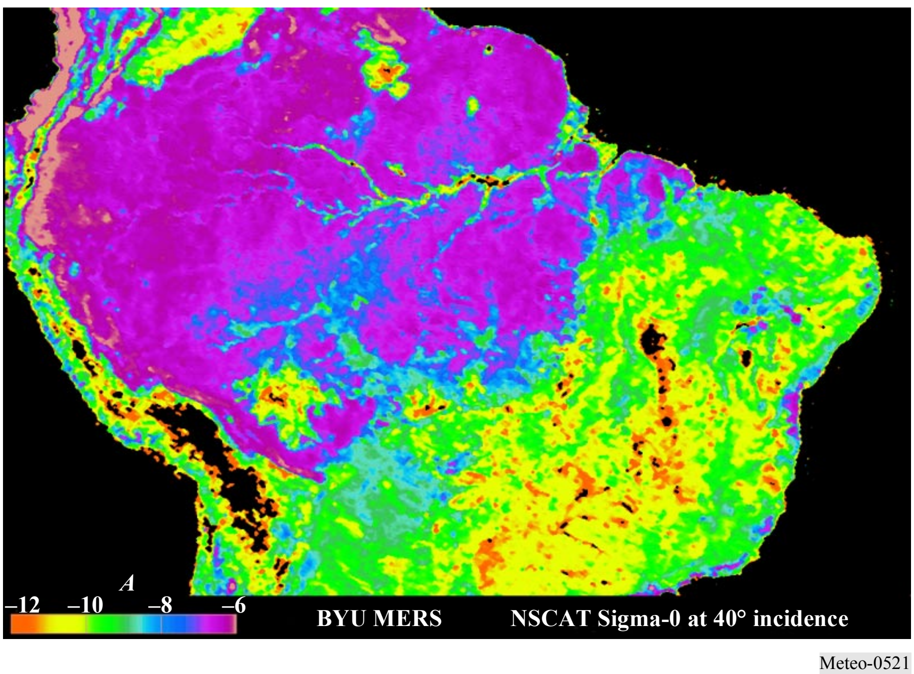



Figure 5-21 shows a radar image from NSCAT of the Amazon rainforest in South America. Other examples of scatterometers used for meteorological purposes are the ERS AMI (wind mode) and METOP Ascat.

FIGURE 5-21

**NSCAT radar image of the Amazon rainforest in South America**



### 5.2.5 Precipitation radars

Precipitation radars provide the precipitation rate over the Earth's surface, typically concentrating on rainfall in the tropics. Figure 5-22 is an illustration of the TRMM satellite.

FIGURE 5-22

**TRMM satellite illustration**

Meteo-0522

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

$$\sigma_b = \pi^5 |K_W|^2 D^6/\lambda^4 = \pi^5 |K_W|^2 Z/\lambda^4 \qquad (5\text{-}4)$$

where:

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

$D$: diameter of the drop

$\lambda$: wavelength of the radar

$Z$: radar reflectivity factor.

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

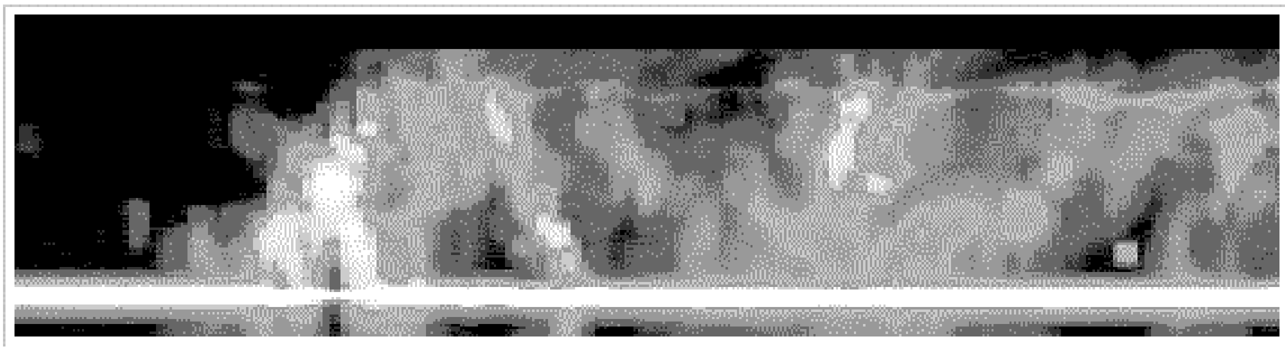
Figure 5-23 shows an example of a vertical cross section of radar reflectivity factor. The narrow RF signal pulse-width provides the needed measurement range resolution. TRMM uses pulse width of 1.6 µs. The allowable minimum precipitation reflectivity degradation determines the allowable interference level.

### 5.2.6 Cloud profile radars

Cloud profile radars provide a three dimensional profile of cloud reflectivity over the Earth's surface. Figure 5-24 shows a representative backscatter reflectivity versus altitude.

FIGURE 5-23

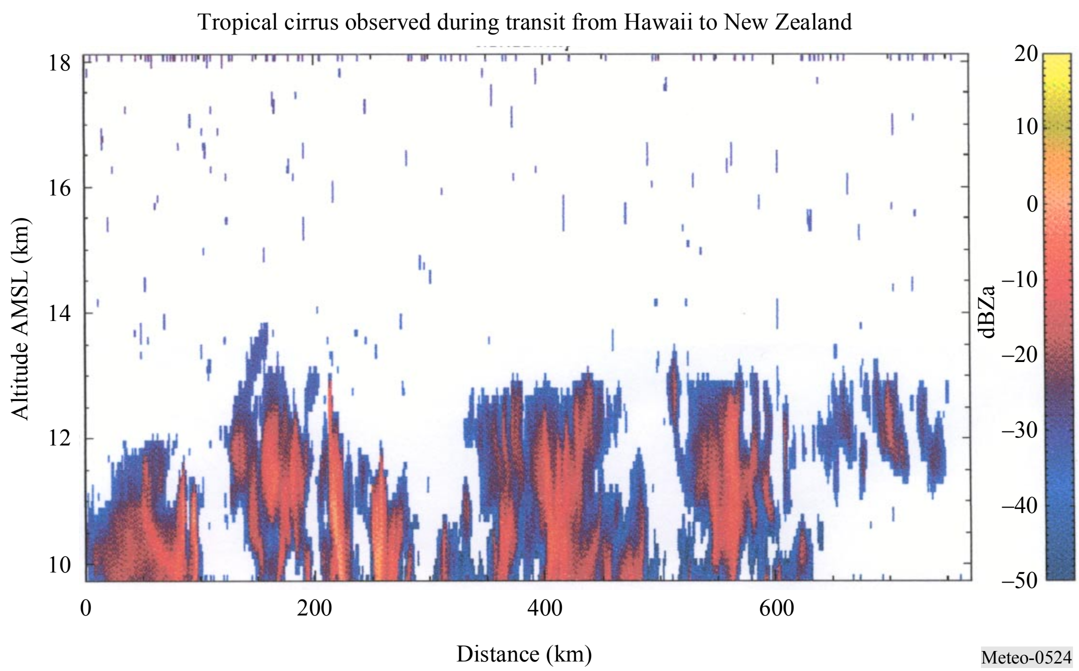
**Synthesized TRMM PR reflectivity from ARMAR reflectivity measurements**



Meteo-0523

FIGURE 5-24

**Example of cirrus cloud reflectivity**




Meteo-0524

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.

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

where:

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

$P_r$: radar transmit power (W)

$G$: antenna gain (numeric)

$t$ : pulse width (µs)

$\theta_r$: 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)

$\lambda$: radar wavelength (cm)

$l$: signal loss due to atmospheric absorption

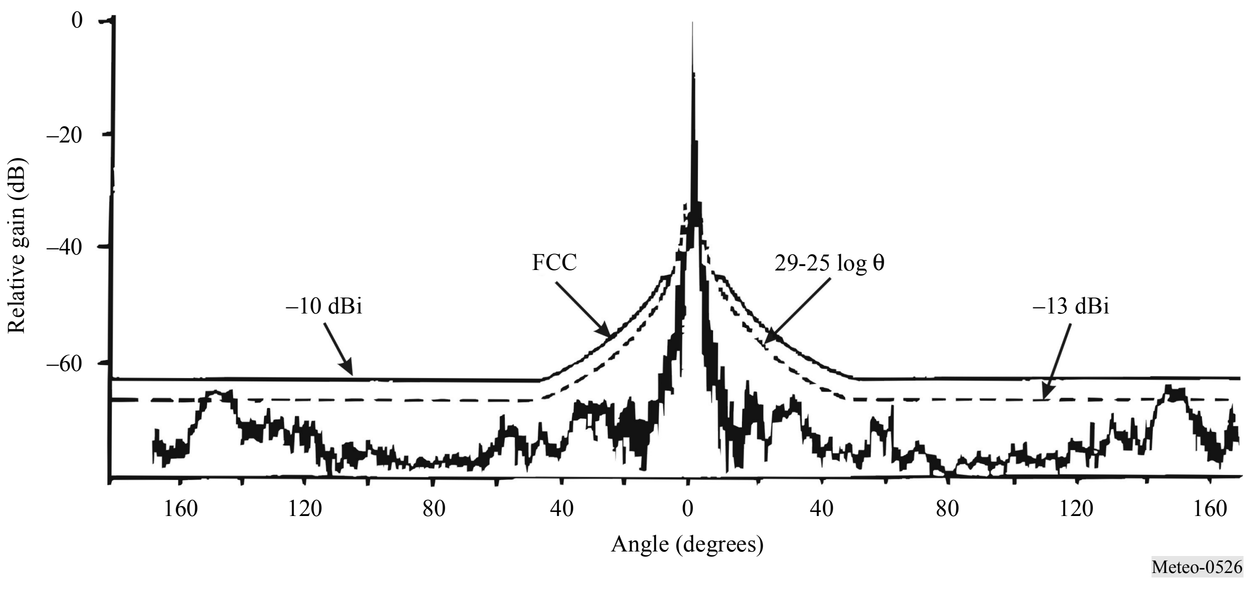
$l_r$: radar system loss.

As can be seen in this expression, 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 5-25 shows the –60 dB sidelobes for a representative antenna. The narrow RF signal bandwidth provides the needed measurement cell resolution. The allowable reflectivity accuracy degradation determines the allowable interference level.

FIGURE 5-25

**Relative gain versus antenna angle**




### 5.2.7 Sensor interference and performance criteria

The criteria for performance and interference are shown below for the various types of active spaceborne sensors:

SAR: 10% degradation of standard deviation of pixel power yields $I/N = –6$ dB with mitigating effects of processing

Altimeter: 4% degradation in height noise yields $I/N = –3$ dB

Scatterometer: Degradation in measurement of normalized radar backscatter coefficient with simulations of measurement scheme yields $I/N = -5$ dB

Precipitation radar: 7% increase in minimum rainfall rate yields $I/N = -10$ dB

Cloud radar: 10% degradation in minimum cloud reflectivity yields $I/N = -10$ dB.

The criteria for performance and interference are summarized in Table 5-11.

TABLE 5-11

**Criteria for performance and interference**

| Sensor type | *I*/*N* criteria (dB) | Availability criteria (%) | |
|---|---|---|---|
| | | Systematic | Random |
| Synthetic aperture radar | –6 | 99 | 95 |
| Altimeter | –3 | 99 | 95 |
| Scatterometer | –5 | 99 | 95 |
| Precipitation radar | –10 | N/A | 99.8 |
| Cloud profile radar | –10 | 99 | 95 |

### 5.2.8 Interference levels

The characteristics of the various types of active spaceborne sensors as shown in Table 5-10 indicate that the transmitted peak power and therefore the power levels received at the Earth's surface will vary significantly in level. Table 5-12 shows the active sensor power density flux levels at the Earth's surface for some typical sensor configurations.

TABLE 5-12

**Typical interference 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 | 1 344 | 1 145 | 350 | 400 |
| PDF (dB(W/m$^2$)) | –59.67 | –77.25 | –78.17 | –46.55 | –31.64 |

### 5.2.9 Compatibility studies

Compatibility studies have been performed in ITU-R for many of the active spaceborne sensor frequency bands. Table 5-13 summarizes which frequency bands and which sensor types in those bands have been analysed for compatibility.

TABLE 5-13

**Compatibility studies by frequency band and sensor type**

| Frequency band (MHz) | Sensor type | | | | |
|---|---|---|---|---|---|
| | SAR | Altimeter | Scatterometer | Precipitation radars | Cloud profile radars |
| 430-440 | (F) | | | | |
| 1 215-1 300 | SIR-C, JERS-1, PALSAR (ALOS) | | | | |
| 3 100-3 300 | ALMAZ | RA2 (F) | | | |
| 5 150-5 250 | RADARSAT-2 (F) | JASON (F) | | | |
| 5 250-5 350 | RADARSAT,<br>ASAR, ERS1/2, ENVISAT ASAR (F) | TOPEX | ERS1/2, NSCAT (F),<br>METOP ASCAT (F) | | |
| 5 350-5 470 | RADARSAT-2 (F) | JASON (F) | | | |
| 8 550-8 650 | (P) | (P) | (P) | | |
| 9 500-9 800 | X-SAR,<br>Okean-O SLR | (P) | (P) | | |
| 9 975-10 025 | | | | | |
| 13 250-13 400 | | JASON | NSCAT, SEAWINDS | TRMM follow-on (F) | |
| 13 400-13 750 | | JASON, ERS1/2 | NSCAT, SEAWINDS,<br>ENVISAT RA-2 (F) | TRMM follow-on (F) | |
| 17 200-17 300 | | | (P) | (P) | |
| 24 050-24 250 | | | | (P) | |
| 35 500-35 600 | | (P) | (P) | TRMM follow-on (F) | |
| 78 000-79 000 | | | | | (P) |
| 94 000-94 100 | | | | | CLOUDSAT (F) |
| 133 500-134 000 | | | | | (P) |
| 237 900-238 000 | | | | | (P) |

*Note*: (F) Future proposed, (P) Postulated, and currently operating otherwise.

### 5.2.10 Current status

The status for allocation for the active spaceborne sensors is summarized in Table 5-14.

TABLE 5-14

**Allocation status for active spaceborne sensors**

| Frequency band (GHz) | User objectives | Allocation status | Allocation needed | Users |
|---|---|---|---|---|
| 0.420-0.470 | Forest monitoring (biomass) | None | PRIMARY or secondary, minimum 6 MHz | P-band SAR |
| 1.215-1.300 | Wave structure, geology, soil moisture, interfer-ometry (DEM) | PRIMARY RR Nos. 5.332 and 5.335 | PRIMARY | L-band SAR (JERS-1, SIR-C, PALSAR) |
| 3.1-3.3 | Geology | Secondary | PRIMARY | S-band SAR, Altimeter (Envisat RA-2 second frequency) |
| 5.15-5.25 | Geology, oceano-graphy, sea ice, land use, inter-ferometry (DEM) | None | PRIMARY | High resolution radar altimeters (Jason) |
| 5.25-5.46 | Geology, oceano-graphy, sea ice, land use, inter-ferometry. (DEM) | PRIMARY RR Nos. 5.447D, 5.448A, B | PRIMARY 5 460-5 570 MHz | SAR, scatterometers, altimeters (AMI, ASCAT, ASAR, ALT/dual, IKAR-N) |
| 8.55-8.65 | High resolution SAR applications (tactical) plus snow and ice | PRIMARY RR Nos. 5.468 and 5.469 | PRIMARY | Not identified |
| 9.5-9.8 | High resolution SAR applications (tactical) plus snow and ice | PRIMARY RR No. 5.476A | PRIMARY | X-band SAR, Okean-O SLR |
| 9.975-10.025 | High resolution SAR applications (tactical) plus snow and ice | Secondary RR No. 5.479 | Not identified | Not identified |
| 13.25-13.75 | Wind, ice, geoid | PRIMARY RR Nos. 5.498A, 501A, B | PRIMARY | Ku-band scatterometers, altimeters (NSCAT, ALT/dual, PR, R225, IKAR-D&N, RA, RA-2, DPR) |
| 17.2-17.3 | Vegetation, snow, rain, wind | PRIMARY RR No. 5.513A | | Rain radars precipitation radar, scatterometers |
| 24.05-24.25 | Rain | Secondary | PRIMARY | Rain radars precipitation radar (IKAR-D & N) |

TABLE 5-14 (*end*)

| **Frequency band (GHz)** | **User objectives** | **Allocation status** | **Allocation needed** | **Users** |
|---|---|---|---|---|
| 35.5-36 | Ice, wind, geoid, snow | PRIMARY<br>RR No. 5.551A | | Altimeters, scatterometers, precipitation radar (IKAR-N, DPR) |
| 78-79 | Altimetry (land and ice) at high spatial resolution | PRIMARY<br>RR No. 5.560 | | Radio altimeters |
| 94.0-94.1 | Cloud profiling | PRIMARY<br>RR No. 5.562 | PRIMARY | Cloud profile radars (ESA CPR, CPR/NASA, IKAR-D & N) |
| 133.5-134 | Cloud profiling | PRIMARY<br>RR No. 5.562E | | Cloud profile radars |
| 237.9-238 | Cloud profiling | PRIMARY<br>RR No. 5.563B | | Cloud profile radars |

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AMSR-E: http://eos-pm.gsfc.nasa.gov/

SMILES: http://smiles.tksc.nasda.go.jp/

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WWW Figure Access Addresses:

SAR: http://www.jpl.nasa.gov/radar/sircxsar/dsea.html

PALSAR/ALOS: http://www.eorc.nasda.go.jp/ALOS

Altimeter: http://ibis.grdl.noaa.gov/SAT/near_rt/enso/topex_97.html

SLR: http://sputnik1.infospace.ru

http://planet.iitp.ru

### ITU-R texts

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

# CHAPTER 6

## OTHER RADIOCOMMUNICATION SYSTEMS FOR METEOROLOGICAL ACTIVITIES

Page

# 6 Introduction

As discussed in Chapter 1 meteorological services need to collect observations from many remote sites, both on land and over the sea. Real time measurements from commercial aircraft are becoming increasingly important for meteorological services. These measurements are required during ascent and descent close to the airports, but also from longer ranges at cruise level heights. Thus, the meteorological observing system is dependent on many other radiocommunication services in addition to the MetSat and MetAids 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. Meteorological services are supplied to support maritime operations and to support aviation operations worldwide. The broadcasting and dissemination systems for meteorological products also utilize a wide range of radiocommunication services.

Three topics exemplifying the use of the other radiocommunication services will be considered in the following sections:

6.1 Broadcasting and dissemination systems

6.2 Hydrological radio systems

6.3 Other satellite systems

The fixed service is used to support operation of some meteorological systems. These uses will be discussed briefly in section:

6.4 Fixed remote systems

Radiodetermination and radionavigation services have been widely used by meteorologists for many years. In some cases, the meteorological use differs from other uses and may place some additional constraints on the service. This will be discussed in more detail in section:

6.5 Meteorological uses of radionavigation systems

Some uses of the radiofrequency spectrum are not readily accommodated within the current structure of radiocommunication services in ITU. These will be illustrated for two topics in sections:

6.6 Lightning detection and location systems

6.7 Ground based passive remote sensing

## 6.1 Broadcasting and dissemination systems

Of importance equal to the collection and archiving of weather data and the preparation of forecasts is the dissemination of these forecasts. Only by making these predictions available to the public can lives be saved, because only by knowing what is coming, can people 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 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 aircraft. 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.

## 6.2 Examples of hydrological radio systems

### 6.2.1 Introduction

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. Hydrological systems typically are used to measure such things as precipitation, stream height and the depth of snow pack, all of which are useful in predicting flooding and in estimating the availability of water resources. They typically operate in the VHF or UHF bands in the fixed or mobile services.

Annual average flood damage in the United States of America alone now approaches $4 billion. 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.

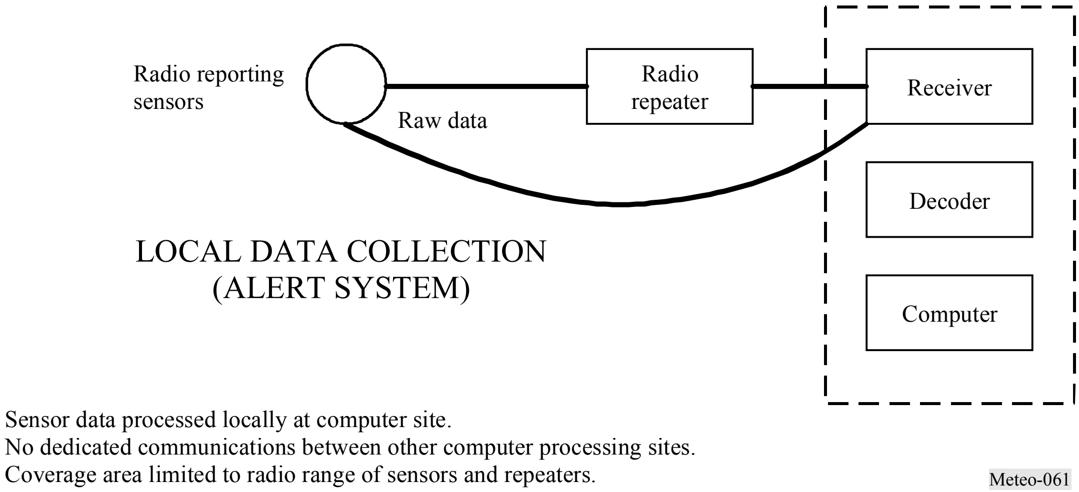
### 6.2.2 Representative hydrological systems

In the United States, the National Weather Service (NWS) is responsible for issuing local and regional flood warnings. The data obtained by the NWS from automated local flood warning systems (ALFWSs) using hydrologic radio frequencies help make warnings timely and accurate. There are over 400 such systems in the United States using 42 hydrologic radio frequencies. These are frequencies in the VHF (162-174 MHz) and UHF (406.1-420 MHz) bands which have been set aside primarily for use by hydrological systems. The number of ALFWSs using radio is expected to increase as additional flash flood systems become operational.

The automated local evaluation in real time (ALERT) system consists of automated event-reporting meteorological and hydrologic sensors, communications equipment, and computer software and hardware. In its simplest form, ALERT sensors transmit coded signals, usually via very high frequency (VHF) and ultra high frequency (UHF) radio, 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 preset criteria are exceeded.

FIGURE 6-1

**Schematic of an ALERT system**




## 6.3 Other satellite systems

Data collection, transmission and dissemination are beginning to be assisted by a number of other satellite systems and the use of such systems is expected to increase in the future. Currently, raw and processed meteorological data are transported worldwide and domestically by the fixed-satellite service (FSS). The newer and still-developing mobile-satellite service (MSS) may some day facilitate data collection, particularly from remote and inaccessible locations. MSS systems are divided into two classes. Those operating below 1 GHz provide inexpensive data-only service and are known as non-voice non-geostationary (NVNG) MSS or little low earth orbiters (LEOs). Systems that provide data and voice and operate their service links (to and from individual users) in the 1-3 GHz range are known as big LEOs.

## 6.4 Fixed remote 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 radionavigation systems

### 6.5.1 Terrestrial services

Meteorologists utilize radionavigation service signals for a variety of purposes. The use of Omega navigation signals (frequencies between 10 to 13 kHz) became widespread for tracking radiosondes in the MetAids service from about 1985 onwards until its termination of operation. This was because the radiosonde systems could be used with simple base station antenna, processing was automated and the systems were easy to maintain in remote locations. Loran-C signals at 100 kHz were also used for the same purpose and the use of Loran-C has increased in areas where suitable coverage has been maintained.

At the time of the closure of the Omega transmitters in 1997, more than 20% of the radiosonde systems in the WMO network had to be changed. Most of these ground systems were modified or replaced to use radiosondes receiving and processing GPS navigation signals.

### 6.5.2 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 and the proposed Galileo system) 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, pilotless 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 § 6.6).

– *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 METOP and NPOESS, and are also being carried on specialized satellites such as COSMIC.

## 6.6 Lightning detection and location systems

The need by operational meteorologists for remote sensing of lightning activity is rapidly increasing. 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 (see Fig. 6-2) 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.

FIGURE 6-2

**Time-lapse photograph of cloud-to-ground lightning near Norman, Oklahoma, United States of America**

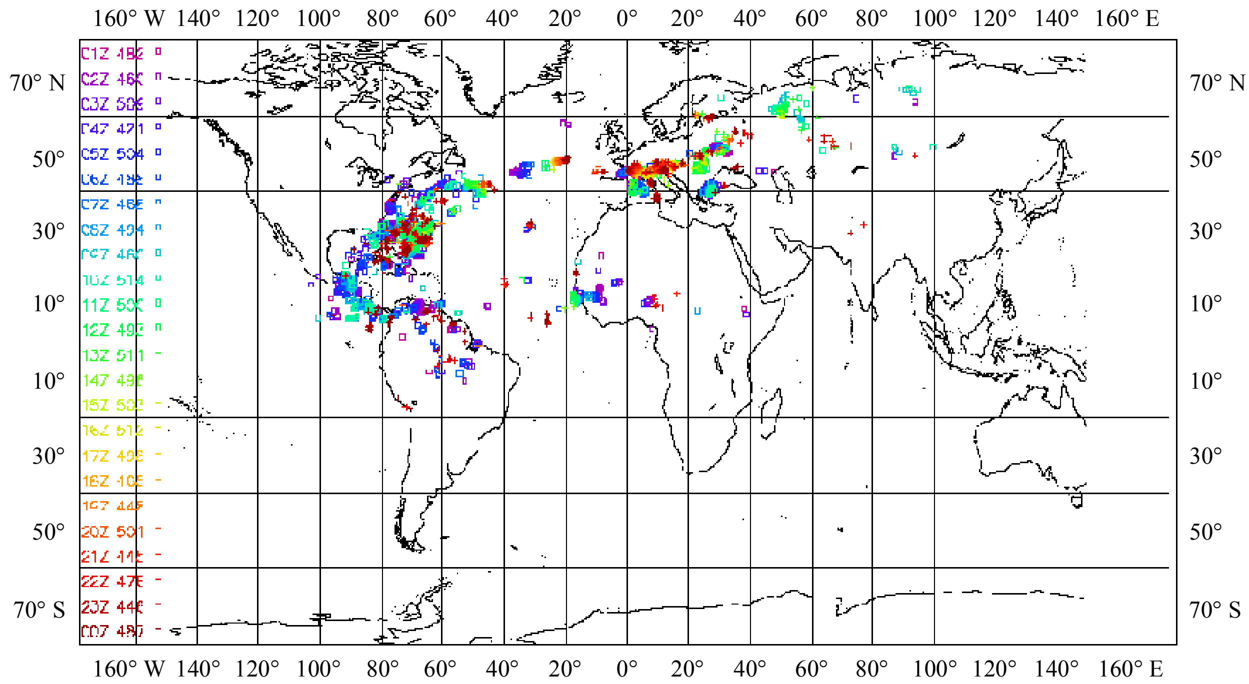
Meteo-062

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 ranges of several thousand kilometres are achieved operationally by observing frequencies centred at 10 kHz (2-15 kHz) (see Fig. 6-3). In this system, the spherics are received at the remote outstations located around Europe [Lee, 1986] 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. Interference is extremely detrimental to the operation of the system and each outstation is equipped with adjustable notch filters to discriminate against local contamination.

FIGURE 6-3

**Map of lightning data for one day for long range system**




11 581 thunderstorm records in this 24 h period

Meteo-063

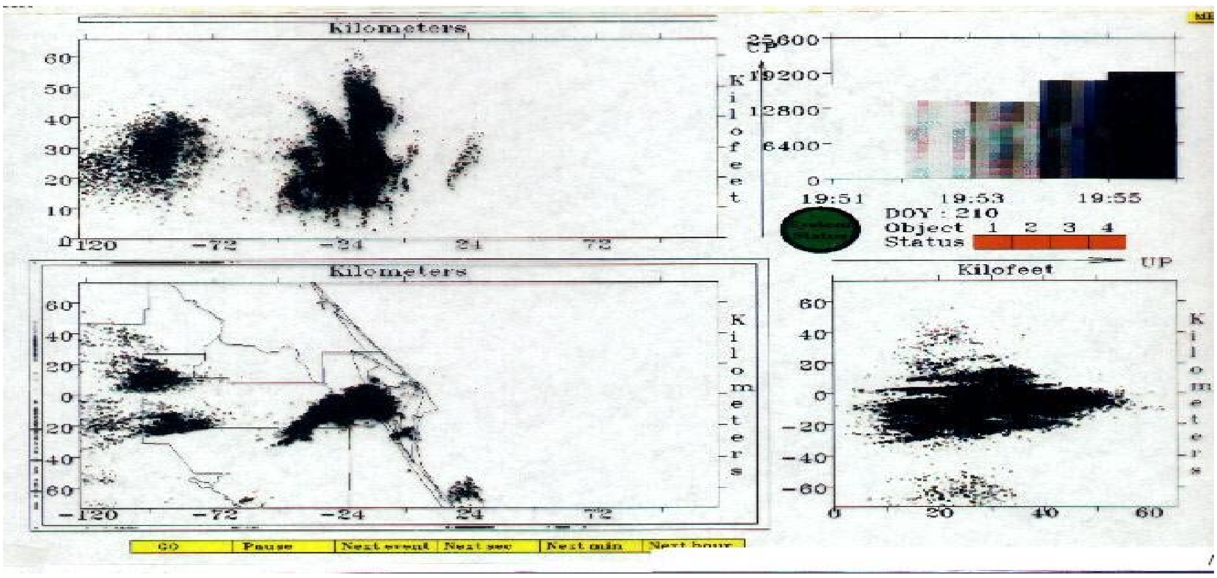
The most widely used operational systems cover a more limited area in detail. In this case, the spherics are observed at higher frequencies centred around 200 kHz (the wideband receivers used are most sensitive in the middle of their range of 1 kHz to 350 kHz), and the sensing sites are usually spaced 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 (LDAR), while SAFIR uses 110 to 118 MHz). The LDAR system developed by NASA is described by [Lennon and Maier, 1991], and the SAFIR system developed in France is discussed by [Kawasaki *et al.*, 1994]. Figure 6-4 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. However, in practice 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. 6-4 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° on its side). A histogram (upper right) displays the data in five one-minute increments.

FIGURE 6-4

**Real-time LDAR display**




Meteo-064

## 6.7 Ground-based remote sensing

Vertical atmospheric sounding using passive remote sensing from satellites has been discussed 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 can 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. Radiometers are now commercially available for this purpose. These 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 in the future may also benefit 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 not identical to those used by satellites. At some frequencies, satellite remote sensing can safely share with terrestrial services, but ground-based radiometers may need protection. The number of ground-based radiometers in operation is still small, but if current developments are successful, larger numbers may be deployed in the 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, is also expected to benefit from a significant number of ground-based radiometry sites.

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# ANNEX 1

## ACRONYMS AND ABBREVIATIONS COMMONLY USED IN METEOROLOGY

**A**

| | |
|---|---|
| A/D | Analog-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 | Analog-to-Digital Converter |
| ADP | Automatic Data Processing |
| ADPE | Automatic Data Processing Equipment |
| ADEOS | Advanced Earth Observation Satellite (Japan) |
| 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 Consultative Committee on Radio (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 |
| 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 | Comision 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 |
| CrMIS | Cross-track Microwave Imager-Sounder (NPOESS instrument) |
| CrIS | Cross-track Infrared 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 Color Scanner |

**D**

| | |
|---|---|
| D/A | Digital-to-Analog |
| 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 |
| EOS | Earth Observation Satellites |
| EPIRB | Emergency Position-Indicating Radio Beacon |
| 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 | Enhanced Thematic Mapper |
| ETM | Engineering Test Model |
| ETS | Engineering Test Satellite |
| EUMETSAT | European Organization for the Exploitation of Meteorological Satellites |
| EUV | Extreme Ultraviolet |

**F**

| | |
|---|---|
| FAX | Facsimile |
| FC | False Color |
| FCC | False Color 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 | Groupemant pour le Developpement de la Teledetection Aerospatiale |
| 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 |
| 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/S | Imager and Sounder |
| I/O | Input/Output |
| 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 |
| kb | kilobit(s) |
| kB | kilobyte(s) |
| KBPS or Kb/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 |
| Mbps | Megabits per second |
| MBps | 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 |

| | |
|---|---|
| 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 |
| MTF | Modulation Transfer Function |
| MTBF | Mean Time Between Failures |
| 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 |
| 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 Color 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 |
| PWM | Pulse-width Modulation |

**Q**

| | |
|---|---|
| QC | Quality Control |
| QPSK | Quadrature PSK |

**R**

| | |
|---|---|
| R | Rayleighs |
| 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 |
| $S/N_0$ | Signal-to-Noise density ratio |
| S-VAS | Stretched Visible Infrared Spin Scan Radiometer Atmospheric Sounder |
| S-VISSR | Stretched Visible Infrared Spin Scan Radiometer |
| $S/N$ | Signal-to-Noise ratio |
| 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/OMS | Subcommittee on Operational Meteorological Satellites |
| SC/OES | Subcommittee on Operational Environmental Satellites |
| $SC/N_0$ | Subcarrier-to-Noise density ratio |
| 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 | Steradian |
| SR | Scanning Radiometer |
| 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&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 |
| TIR | Thermal Infrared |
| TIP | TIROS Information Processor |

| | |
|---|---|
| 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 Radiocommunications 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 |

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