

Handbook

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

Edition 2008

Radiocommunication Bureau



World
Meteorological
Organization



International
Telecommunication
Union



Handbook

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**World
Meteorological
Organization**



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PREFACE

“Climate change is the moral challenge of our generation...”

Ban Ki-moon, UN Secretary-General

WMO XV World Meteorological Congress 2007, in Resolution 4 (Cg-XV):

Considering:

The crucial importance of radio-frequency bands for meteorological and related environmental operations and research, and for disaster risk reduction;

...

Stressing

that some radio-frequency bands are a unique natural resource due to their special characteristics and natural radiation for passive sensing of the atmosphere and the Earth surface that deserve absolute protection;

...

Urges all Members

to do their utmost at national, regional and international levels to ensure the availability and protection of suitable radio-frequency bands;

...

Appeals to the International Telecommunication Union and its Member Administrations

- (1) To ensure the absolute protection of the passive sensing radio-frequency bands;
- (2) To give due consideration to the WMO requirements for radio-frequency allocations and regulatory provisions for meteorological and related environmental operations and research;

...

ITU World Radiocommunication Conference (Geneva, 2007), in Resolution 673 (WRC-07):

“considering

a) that *in situ* and remote Earth observation capabilities depend on the availability of radio frequencies under a number of radio services, allowing for a wide range of passive and active applications on satellite- or ground-based platforms;

...

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

...

“resolves to invite ITU-R

to carry out studies on possible means to improve the recognition of the essential role and global importance of Earth observation radiocommunications applications and the knowledge and understanding of administrations regarding the utilization and benefits of these applications,”

....

Between 1980 and 2005, more than 7 000 natural disasters worldwide took the lives of over 2 million people and produced economic losses estimated at over 1.2 trillion US dollars. Ninety per cent of these natural disasters, 72% of casualties and 75% of economic losses were caused by weather-, climate- and water-related hazards, such as droughts, floods, severe storms and tropical cyclones. At present, radio-based applications such as remote sensors provide the main source of information about the Earth’s atmosphere and surface. In turn, this information is used for climate, weather and water monitoring, prediction and warnings, natural disasters risk reduction, support of disaster-relief operations and for planning preventive measures for adapting to and mitigating the negative effects of climate change.

For 135 years, there has been excellent collaboration and partnership between WMO and ITU. Whilst WMO focuses its efforts on meeting the needs for environmental information and the corresponding radio frequency spectrum resources, ITU, as international steward of the spectrum, allocates the necessary radio frequencies to allow the interference-free operation of radio-based applications and radiocommunication systems (terrestrial and space) used for climate monitoring and prediction, weather forecasting and disaster early warning and detection.

Successive ITU World Radiocommunication Conferences have taken into account the needs of WMO to ensure the availability and protection of radio-frequency bands for observation tools such as radiosondes, weather and wind profiler radars and spaceborne infrared and microwave sounders.

Other information and communication technologies (ICT) not considered in this handbook, such as wired and satellite telecommunication links and computers, are also essential parts of the WMO Information System (WIS). Many ITU technical standards (ITU-R and ITU-T Recommendations) are being used for the development and operation of this system.

This new version of the Handbook Use of Radio Spectrum for Meteorology: Weather, Water and Climate Monitoring and Prediction is further proof of the excellent cooperation between ITU and WMO. It has been developed jointly by experts of ITU-R Working Party 7C under the chairmanship of Mr. E. Marelli (ESA) of ITU-R Radiocommunication Study Group 7 (Science Services), and the Steering Group on Radio Frequency Coordination (SG-RFC) of the WMO Commission for Basis Systems (CBS), under the chairmanship of Mr. P. Tristant (Meteo France).

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



Mr. Michel JARRAUD
Secretary-General
World Meteorological Organization



Dr. Hamadoun TOURÉ
Secretary-General
International Telecommunication Union

TABLE OF CONTENTS

	<i>Page</i>
FOREWORD.....	vii
INTRODUCTION.....	ix
CHAPTER 1 – GENERAL STRUCTURE OF METEOROLOGICAL SYSTEMS	1
CHAPTER 2 – METEOROLOGICAL SATELLITE SERVICE (MetSat)	7
CHAPTER 3 – METEOROLOGICAL AIDS SERVICE	17
CHAPTER 4 – METEOROLOGICAL RADARS	33
CHAPTER 5 – PASSIVE AND ACTIVE SPACEBORNE REMOTE SENSING FOR METEOROLOGICAL ACTIVITIES	61
CHAPTER 6 – OTHER RADIOCOMMUNICATION SYSTEMS FOR METEOROLOGICAL ACTIVITIES	89
ANNEX 1 – ACRONYMS AND ABBREVIATIONS COMMONLY USED IN METEOROLOGY	97

FOREWORD

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

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

Meteorology is a crucial part of our everyday life and has many connections with our daily preoccupations. Weather forecast is probably the most popular programme on TV or radio today. Not only it affects the way we dress or decide what to do, it also has many implications on public safety. Public transports are highly dependant on meteorology, being able to accurately predict weather is essential to provide a high level of safety. In this period of great meteorological and climate disturbances, this activity also plays a major role in the prediction, detection and mitigation of negative effect of natural disasters.

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

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

Effective and prudent management of allocated frequency bands is paramount to maintaining and enhancing the quality and accuracy of weather and weather-related predictions. It is essential to understand for instance that if some the frequency bands currently allocated for meteorological purposes were to be used by to other radio systems that are incompatible with meteorological radio systems, then these bands could be rendered unusable for weather, climate and/or disaster prediction systems, thus making corresponding forecasts extremely difficult and sometimes impossible.

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

The Handbook could not have been completed without the contributions from many administrations participating in Study Group 7 and SG-RFC. 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 Chairmen of ITU-R WP 7C, Mr. Edoardo Marelli (ESA) and WMO SG-RFC, Mr. Philippe Tristant (Meteo France) for their leadership of this project. Our special gratitude is also due to Mr. A. Vassiliev of the Radiocommunication Bureau who has played an important role in the publication of the Handbook.

Vincent Meens
Chairman, Radiocommunication Study Group 7

INTRODUCTION

Timely warning of impending natural and environmental disasters, accurate climate prediction and detailed understanding of the status of global water resources: these are all critically important everyday issues for the global community. The National Meteorological Services around the world are responsible for providing this information, which is required for the protection of the environment, economic development (transport, energy, agriculture, etc.) and the safety of life and property.

Radio frequencies represent scarce and key resources used by National Meteorological Services to measure and collect the observation data upon which analyses and predictions, including warnings, are based or processed, and to disseminate this information to governments, policy makers, disaster management organisations, commercial interests and the general public.

On a more general basis, the utmost importance of radio frequencies for all Earth Observation activities is also to be stressed, in particular with regards to the global warming and climate change activities.

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

Radio frequencies therefore represent a scarce and key resource to the meteorological community.

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

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

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

Meteorological users of the spectrum must remain vigilant and increasingly address issues concerning sharing of the spectrum with other radio-communications services. In recognition of the prime importance of the specific radiocommunication services for meteorological and related environmental activities required for the safety of life and property, the protection of the environment, climate change studies and scientific research, the World Meteorological Organisation (WMO) Resolution 4 (Cg-XV) appeals to the International Telecommunication Union (ITU) and its Member Administrations:

- to ensure the availability and absolute protection of the radio-frequency bands which, due to their special physical characteristics, are a unique natural resource for spaceborne passive sensing of the atmosphere and the Earth surface,
- to give due consideration to the WMO requirements for radio frequency allocations and regulatory provisions for meteorological and related environmental operations and research.

In this respect, the last World Radiocommunication Conferences (WRC-03 and WRC-07) secured several relevant frequency allocations, in particular related to the protection satellite passive sensing, under the Earth exploration-satellite service (EESS) (passive). Likewise, future WRCs, such as the next one in 2011, will look for extended frequency allocations for several science services that will result in improvements and/or safeguarding of the meteorological.

Recent sharing issues concerning frequency bands used by meteorological systems resulted in a profusion of studies within the ITU and its Radiocommunication Sector (ITU-R) seeking to determine how spectrum can be made available for new radio applications. 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 and future meteorological systems. In some instances, these studies have shown that co-channel sharing was not possible and that 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 and that, in particular, frequency bands used by passive sensing are dictated by the laws of physics and cannot be retrieved in other parts of the spectrum.
- If necessary, can financial assistance be provided by the potentially profitable new technologies? And how these potential profits compare to the economical and societal impacts of meteorology?
- 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 “Remote Sensing” of Radiocommunication Study Group 7 and the WMO Steering Group on Radio Frequency Coordination (SG-RFC) have prepared the present Handbook that is intended to serve as a guide to: the professional users of radio-based meteorological systems data; to the people and governments served by these meteorological systems and to the radiocommunications community, including regulators and wireless telecommunications industry.

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

- 1 General structure of meteorological systems
- 2 Meteorological satellite service systems
- 3 Meteorological aids service systems, mainly radiosondes
- 4 Ground-based meteorological radars, including weather radars and wind-profiler radars
- 5 Passive and active spaceborne remote sensing for meteorological activities
- 6 Other radiocommunication systems for meteorological activities

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

CHAPTER 1**GENERAL STRUCTURE OF METEOROLOGICAL SYSTEMS**

	<i>Page</i>
1.1 Meteorological systems of the World Weather Watch	2
1.1.1 Global Observing System	2
1.1.1.1 Surface observing.....	3
1.1.1.2 Upper-air observing	3
1.1.1.3 Radar observations.....	4
1.1.1.4 Observing stations at sea.....	4
1.1.1.5 Observations from aircraft	4
1.1.1.6 Observations from satellites.....	4
1.2 Observing systems of other WMO programmes.....	5
1.2.1 WMO Global Atmosphere Watch.....	5
1.2.2 Global Climate Observing System.....	5
1.2.3 Hydrology and water resources programme	6
1.3 Future plans for WMO observing systems: the WMO Integrated Global Observing Systems (WIGOS).....	6

1.1 Meteorological systems of the World Weather Watch

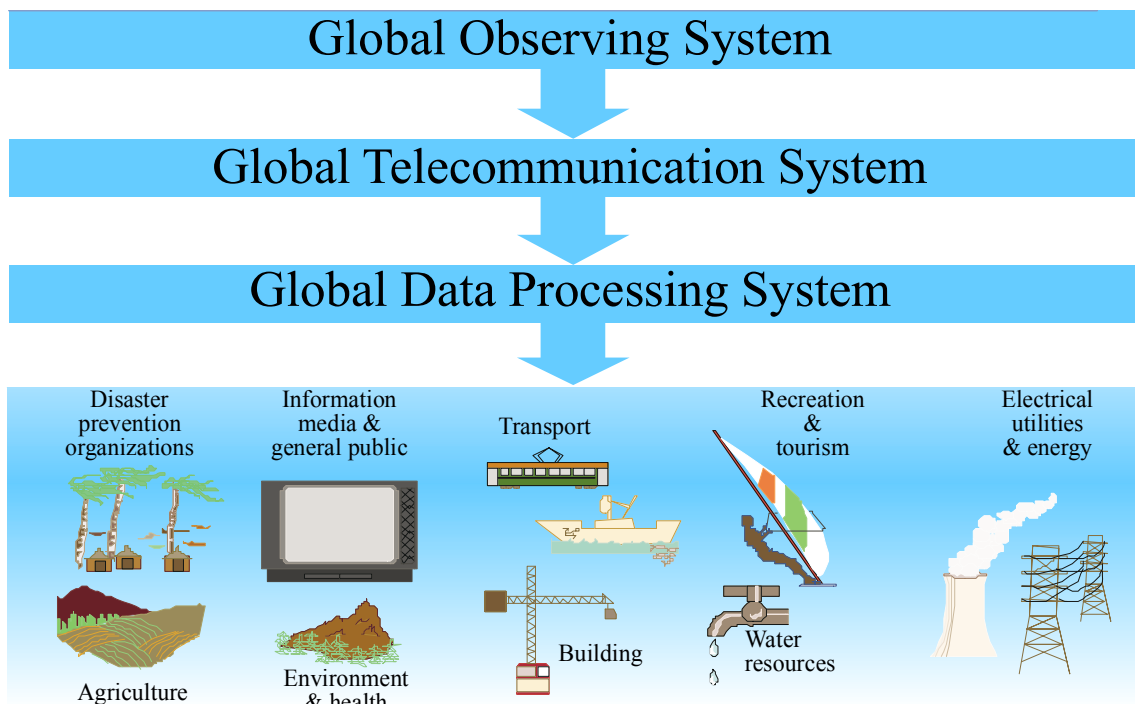
To analyze, warn and predict the weather, modern meteorology depends upon near instantaneous exchange of weather information across the entire globe. The World Weather Watch (WWW), the core of the WMO Programmes, combines observing systems, telecommunication facilities, and data-processing and forecasting centres – operated by the 187 Member States – to make available meteorological and related geophysical information needed to provide efficient services in all countries.

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

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

- The **Global Observing System (GOS)** provides high-quality, standardized observations of the atmosphere and ocean surface from all parts of the globe and from outer space.
- The **Global Telecommunication System (GTS)** provides for the real-time exchange of meteorological observational data, processed products, and related information between national meteorological and hydrological services.
- The **Global Data Processing and Forecasting System** provides processed meteorological products (analysis, warnings, and forecasts) that are generated by a network of World Meteorological Centres and specialized Regional Meteorological Centres.

FIGURE 1-1
World Weather Watch systems



Meteo-01-1

1.1.1 Global Observing System

The Global Observing System (GOS) is the primary source of technical information on the world's atmosphere, and is a composite system of complex methods, techniques and facilities for measuring meteorological and environmental parameters. GOS ensures that critical information is available to every

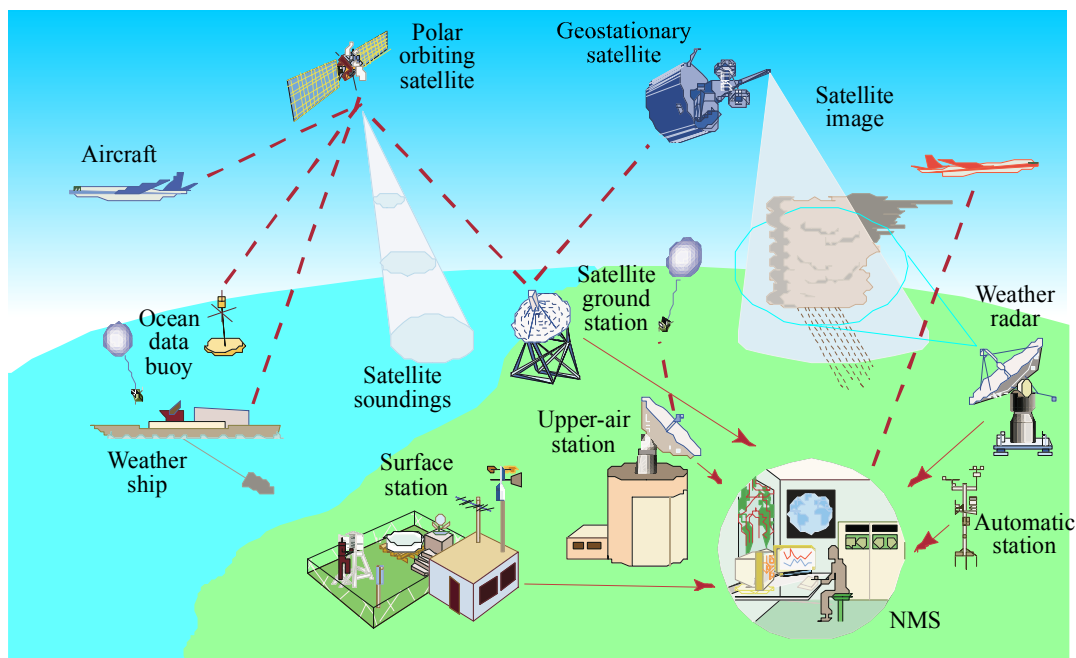
country to generate weather analyses, forecasts and warnings on a day-to-day basis. As shown in Fig. 1-2, GOS is comprised of observing stations located on land, at sea, on aircraft, and on meteorological satellites.

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

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

Detailed information on GOS is available at: <http://www.wmo.int/pages/prog/www/OSY/GOS.html>.

FIGURE 1-2
WMO Global Observing System GOS



Meteo-01-2

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) Surface Network.

1.1.1.2 Upper-air observing

From a network of roughly 900 upper-air stations around the world representing about 800 000 yearly lunches, radiosondes attached to free-rising balloons take measurements of pressure, wind velocity, temperature, and humidity from just above ground to heights up to 30 km. In ocean areas, radiosonde observations are taken by 15 ships, which mainly ply the North Atlantic, fitted with automated shipboard upper-air sounding facilities. A subset of upper-air stations, specially fitted for monitoring the climate, comprises the GCOS Upper-air Network.

1.1.1.3 Radar observations

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

1.1.1.4 Observing stations at sea

Over the oceans, the GOS relies on ships, moored and drifting buoys, and stationary platforms. Observations made by about 7000 ships recruited under the WMO Voluntary Observing Ship Programme, collect the same variables as land stations with the important additions of sea surface temperature and wave height and period. The operational drifting buoy programme comprises about 900 drifting buoys providing 12000 sea surface temperature and surface air pressure reports per day.

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

1.1.1.5 Observations from aircraft

Over 3000 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 dramatically in recent years to an estimated 300000 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 space-based Global Observing System includes constellations of operational geostationary and low Earth orbit (near-polar-orbiting) observation satellites as shown on Fig. 1-3. A list of current operational meteorological satellites and their parameters is available at:

GEO satellites: <http://www.wmo.int/pages/prog/sat/GOSgeo.html>

LEO satellites: <http://www.wmo.int/pages/prog/sat/GOSleo.html>.

In addition, a number of Research & development (R&D) satellites (e.g. Aqua, CBERS, CloudSat, ERS, SPOT, TRMM, Landsat, QuikSCAT, etc.) also include specific meteorological or climatological payload that are also contributing to the GOS. A list of current R&D satellites and their parameters is available at:

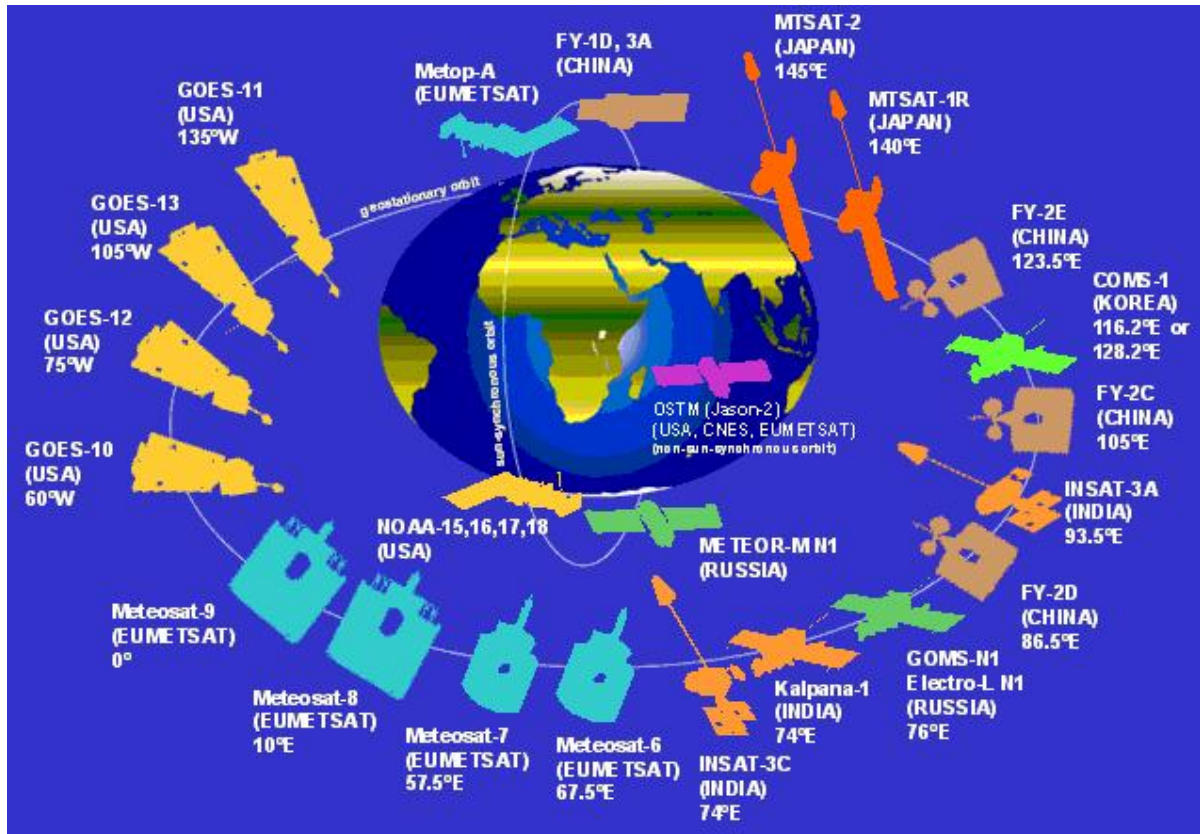
<http://www.wmo.int/pages/prog/sat/GOSresearch.html>.

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

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

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

FIGURE 1-3
Constellation of meteorological satellites of WMO Global Observing System (status 2008)



Meteo-01-3

1.2 Observing systems of other WMO programmes

1.2.1 WMO Global Atmosphere Watch

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

1.2.2 Global Climate Observing System

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

1.2.3 Hydrology and water resources programme

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

1.3 Future plans for WMO observing systems: the WMO Integrated Global Observing Systems (WIGOS)

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

- Increasing interoperability between systems with particular attention given to space-based and *in-situ* components of the systems.
- Addressing the needs of the atmospheric, hydrologic, oceanographic, cryospheric and terrestrial domains within the operational scope of a comprehensive integrated system.
- Ensuring broader governance frameworks and improving WMO management and governance.

CHAPTER 2

METEOROLOGICAL SATELLITE SERVICE (MetSat)

		<i>Page</i>
2.1	Definition of the meteorological satellite service (MetSat) and its frequency allocations....	8
2.1.1	General concept of MetSat satellite systems.....	8
2.2	MetSat systems using geostationary (GSO) satellites.....	10
2.2.1	GSO MetSat raw image sensor data transmissions.....	10
2.2.2	GSO MetSat data dissemination	10
2.2.2.1	High Resolution Image (HRI) dissemination.....	10
2.2.2.2	Stretched Visible Infrared Spin Scan Radiometer (S-VISSR).....	11
2.2.2.3	Geostationary Operational Environmental Satellites (GOES) Variable (GVAR)	11
2.2.2.4	Weather Facsimile (WEFAX).....	11
2.2.2.5	Low Rate Information Transmission (LRIT).....	12
2.2.2.6	High Rate Information Transmission (HRIT).....	12
2.2.3	GSO MetSat Data Collection Platforms (DCPs).....	12
2.3	MetSat systems using non-GSO satellites.....	12
2.3.1	Non-GSO MetSat raw instrument data transmissions.....	13
2.3.2	Non-GSO MetSat data dissemination	13
2.3.2.1	Automatic Picture Transmission (APT).....	13
2.3.2.2	Low Resolution Picture Transmission (LRPT).....	13
2.3.2.3	High Resolution Picture Transmission (HRPT).....	13
2.3.2.4	Low Rate Data (LRD).....	14
2.3.3	Non-GSO MetSat Data Collection Systems (DCSs).....	14
2.4	Alternative data dissemination mechanisms	14

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

The meteorological satellite service (MetSat) is defined in No. 1.52 of the Radio Regulations (RR) as “an Earth exploration-satellite service for meteorological purposes”. It allows the radiocommunication operation between earth stations and one or more space stations 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 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;
- alternative data dissemination to users.

Table 2-1 indicates the radio frequency (RF) bands that are allocated for RF data transmission in the framework of the MetSat.

TABLE 2-1

Frequency bands for use by meteorological satellites for data transmission

Frequency band (MHz)	MetSat allocations
137-138	Primary for space-to-Earth direction
400.15-401	Primary for space-to-Earth direction
401-403	Primary for Earth-to-space direction
460-470	Secondary for space-to-Earth direction
1 670-1 710	Primary for space-to-Earth direction
7 450-7 550	Primary for space-to-Earth direction, geostationary satellites only
7 750-7 850	Primary for space-to-Earth direction, non-geostationary satellites only
8 025-8 400	Primary for space-to-Earth direction for Earth exploration-satellites (Note 1)
8 175-8 215	Primary for Earth-to-space direction
18 000-18 300	Primary for space-to-Earth direction in Region 2, geostationary satellites only
18 100-18 400	Primary for space-to-Earth direction in Regions 1 and 3, geostationary satellites only
25 500-27 000	Primary for space-to-Earth direction for Earth exploration-satellites (Note 1)

NOTE 1 – Since the MetSat is a sub-class of the Earth exploration-satellite service, Earth exploration-satellite service allocations (as an example: 25 500-27 000 MHz) can also be used for the operation of MetSat applications.

2.1.1 General concept of MetSat satellite systems

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

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

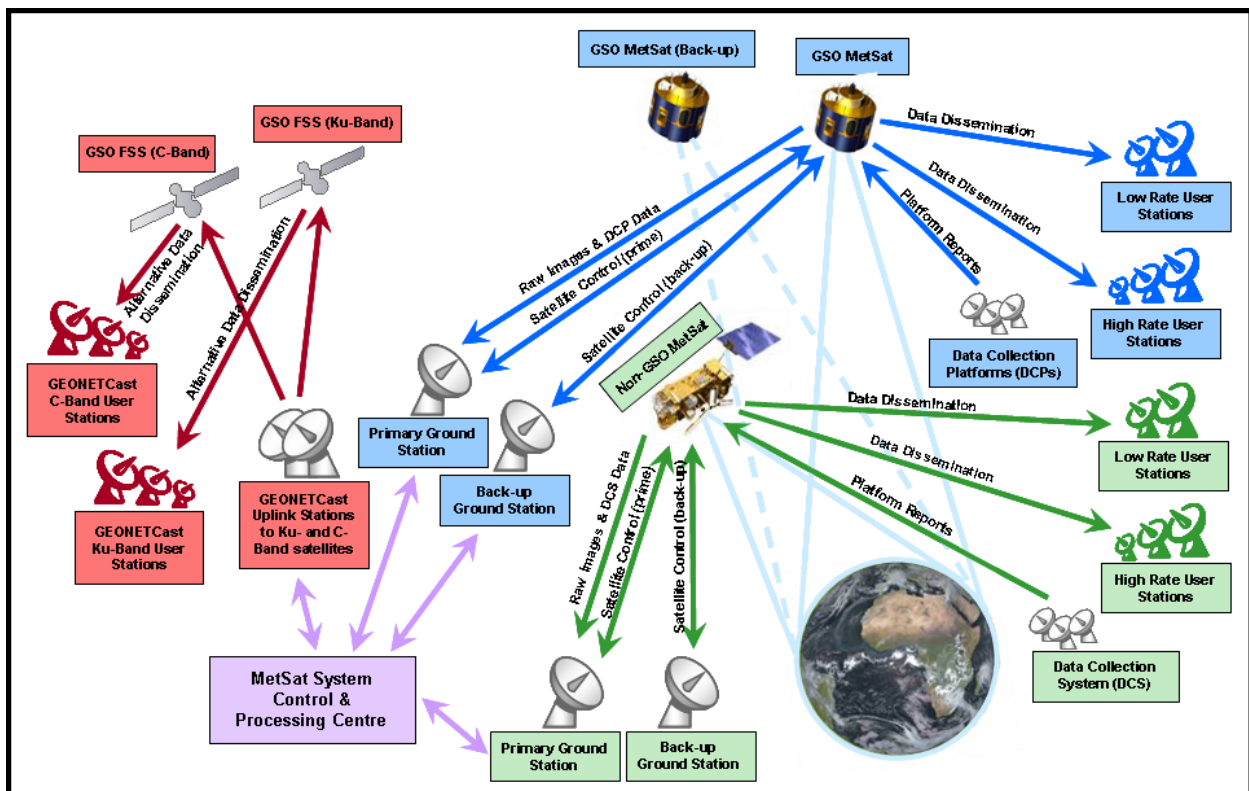
Meteorological satellites also carry Data Collection Systems (DCS), namely Data Collection Platforms (DCPs) on geostationary orbit (GSO) satellite and systems such as Argos on non-geostationary orbit (non-GSO) satellites.

DCPs, typically located on ground, aircrafts, ships and floating buoys, transmit to geostationary meteorological satellites in the band 401-403 MHz data collected on parameters such as surface temperature, wind velocity, rainfall rate, stream height, gases in the atmosphere, and, in the case of floating buoys, oceanic pollutants. They may also transmit their current position, allowing movement to be determined. In addition to the operation of regional DCP channels, MetSat operators also contribute to the International Data Collection System (IDCS) through the operation of international channels. As an additional future application, a dedicated number of IDCS channels can also be allocated for use by an emergency/disaster monitoring system.

Data collection platforms such as of the Argos system transmit to non-GSO MetSat satellites in the 401.580-401.690 MHz band. When installed on buoys and floats, such platforms measure atmospheric pressure, wind speed and direction, sea surface currents and other sea parameters. Among other applications DCS systems on non-GSO satellites are also used to track animal movements as well as to monitor fishing fleets.

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

FIGURE 2-1
General architecture of a MetSat system



2.2 MetSat systems using geostationary (GSO) satellites

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

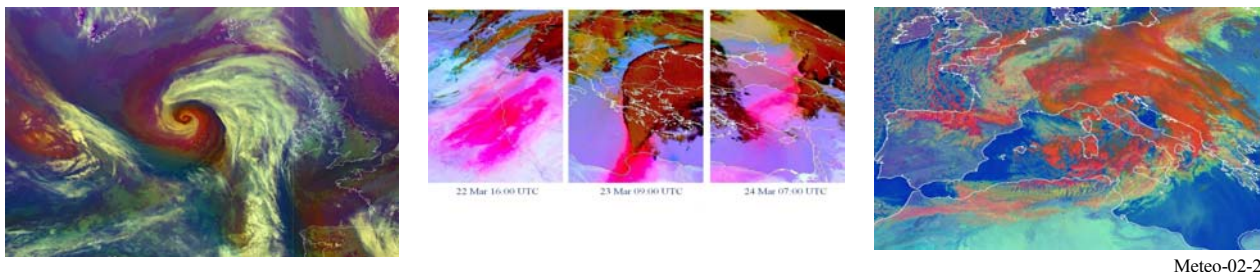
2.2.1 GSO MetSat raw image sensor data transmissions

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

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

FIGURE 2-2

Image of processed data from a GSO meteorological satellite



Meteo-02-2

Cyclonic storm over the North Atlantic
(Meteosat-9 Airmass RGB, 19/05/08 12:00
UTC)

Major dust outbreak from Northern Africa
towards Greece, Turkey, Russia and Kazakhstan
(Meteosat-9, Dust RGB, 22/03/08 - 24/03/08)

Strong mistral and Genoa cyclone with
heavy precipitation over southern Alps
(Meteosat-8 RGB: VIS0.8, IR3.9r, IR10.8,
20/03/07 09:00 UTC)

There 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 m to 18 m diameter and typically operate with a minimum elevation angle of 3°. The figure of merit (G/T) of such stations is of the order of 23 dB/K. Typical bandwidths of the transmissions from present generation GSO MetSat networks are between 2 MHz and 20 MHz depending on the characteristics of the instrument and the modulation methods employed.

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

For next generation GSO MetSat systems (to be operational around 2015) the data rates and the associated bandwidth requirements for the downlink of instrument data will significantly increase (in the order of 100 to 300 Mbit/s). Thus higher frequencies such as the bands 7 450-7 550 MHz, 18.0-18.3 GHz (Region 2), 18.1-18.4 GHz (Regions 1 and 3), 25.5-27 GHz will need to be used.

2.2.2 GSO MetSat data dissemination

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

2.2.2.1 High Resolution Image (HRI) dissemination

The HRI dissemination service operates on the first generation Meteosat spacecraft (Meteosat-6 and Meteosar-7). 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 57.5° East and 67.5° East). Data transmissions contain high-resolution

images including calibration and navigation information. Primary users are national meteorological centres, universities, private forecasters, and television broadcasters.

HRI data dissemination to the users is performed 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°.

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

The S-VISSR service is operated by the satellites FY-2C, -2D and -2E of the Chinese GSO MetSat system Feng-Yun-2.

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

S-VISSR transmissions are performed in the sub-band 1 683-1 690 MHz. 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 antennas is 5°.

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

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

2.2.2.4 Weather Facsimile (WEFAX)

The analogue WEFAX service still used today is in the process of being replaced by digital low rate information transmission (LRIT) service on second-generation meteorological satellite systems. The WEFAX service consists of analogue transmissions to low-cost meteorological user stations within the reception area of meteorological satellites. The WEFAX service parameters were defined and agreed by the Co-ordination Group for Meteorological Satellites (CGMS), a forum for the exchange of technical information on geostationary and polar-orbiting meteorological satellite systems. WEFAX services are operated by Meteosat-6 and Meteosat-7 as well as FY-2C, -2D and 2E.

The World Meteorological Organization (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) 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°, and use antennas of 1.2 m diameter with a figure of merit (G/T) of 2.5 dB/K. Content of WEFAX transmissions are sectors of satellite imagery, meteorological products in pictorial presentation, test images and administrative messages containing alpha-numerical information in pictorial form.

2.2.2.5 Low Rate Information Transmission (LRIT)

LRIT is a new service that was initiated in 2003 on GOES geostationary meteorological satellites for transmission to low cost user stations. This service is intended to replace the WEFAX service on other GSO MetSat satellites, serving a similar user community. It is expected that there will be thousands of user stations called low rate user stations (LRUS).

Transmissions of LRIT are performed in the sub-band 1690-1698 MHz with centre frequencies around 1691 MHz. The bandwidth is up to 600 kHz. User station antennas have diameters between 1.0 m and 1.8 m and are operated with a minimum elevation angle of 3°. The figure of merit for LRUS is 5-6 dB/K depending on the user station location.

2.2.2.6 High Rate Information Transmission (HRIT)

HRIT service was introduced in January 2004 on with the operation of the first satellite (Meteosat-8) of the Meteosat second generation series satellites. With the start of operation of the Japanese MTSAT-1R in June 2005, the HRI and S-VISSR services were replaced by the HRIT service of MTSAT.

The HRIT service is operated in the sub-bands 1684-1690 MHz or 1690-1698 MHz. The antenna size for high rate user station (HRUS) and MDUS is 4 m and the minimum elevation angle is 3°. The figure of merit for the user stations is 12-14 dB/K depending on the user station location.

2.2.3 GSO MetSat Data Collection Platforms (DCPs)

Data collection systems are operated on meteorological satellites for the collection of meteorological and other environmental data from remote DCPs. Transmissions from each DCP to a meteorological satellite are in the frequency band 401-403 MHz. DCPs are operated in time sequential mode. The transmission time slots are typically 1 min. Transmission rates are 100 bit/s. Higher data rate DCPs (300 bit/s and 1200 bit/s) began operation in 2003 and are expected to increase rapidly in the near future. Channel bandwidths of these high rate DCPs are 0.7510 W kHz or 2.2510 W kHz for 300 and 1200 bit/s, respectively.

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

The DCPs reporting to geostationary MetSats use frequencies in the 401.1-402.4 MHz range, with 402-402.1 MHz for international use (33 channels of 3 kHz in bandwidth). By using narrow bands (as small as 0.75 kHz) and by shortening the reporting times to typically 10 s, it is possible to receive data from a large number of these platforms. For example in the case of GOES satellites, in 2007, there were around 27000 GOES DCPs and up to 400000 messages per day, with these numbers anticipated to further increase significantly. Such increased use will possibly necessitate expanding spectrum usage to higher frequencies, moving toward 403 MHz for these reporting platforms.

2.3 MetSat systems using non-GSO satellites

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

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

Figure 2-3 provides examples of an Advanced Very High Resolution Radiometer (AVHRR) flown on operational non-GSO MetSat systems taking global visible, near-infrared and infrared imagery of clouds, oceans and land surfaces. Examples of passive and active sensors observing in the microwave spectral region operated on non-GSO MetSat systems are provided in Chapter 5.

FIGURE 2-3
Samples of image by an advanced very high resolution radiometer



2.3.1 Non-GSO MetSat raw instrument data transmissions

Raw data from some polar-orbiting meteorological satellites are transmitted in the frequency band 7750-7850 MHz to main stations located at high latitudes. The transmissions takes place in bursts as each satellite overpasses its main station, with the transmitters switched off at other times. Other non-GSO MetSat systems use or will use the frequency band 8025-8400 MHz (e.g. FY-3, METEOR and NPP) or 25.5-27 GHz (e.g., NPOESS) for the downlink of the raw instrument data.

2.3.2 Non-GSO MetSat data dissemination

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

2.3.2.1 Automatic Picture Transmission (APT)

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

APT transmissions are based on an analogue modulation scheme. Transmissions are in four sub-bands of the 137-138 MHz band, with typical bandwidths of 30-50 kHz, but may be up to 175 kHz. Future APT transmissions will be restricted to two sub-bands in the 137-138 MHz band: sub-bands 137.025-137.175 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 (LRPT)

The LRPT service is replacing the APT application on most non-GSO MetSat systems. LRPT is based on digital transmission schemes and makes use of the same frequency bands as those currently used for APT. The bandwidth is also up to 175 kHz.

2.3.2.3 High Resolution Picture Transmission (HRPT)

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

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

There is also an Advanced HRPT (AHRPT) application that is intended to replace HRPT on meteorological satellites in the future. Satellite operators may convert to this new service or may choose to continue HRPT transmissions for some time.

AHRPT transmissions will be introduced in the same band as it is used by the other HRPT systems. The bandwidth will be between 4.5 and 5.6 MHz. AHRPT reception stations will receive with minimum elevation angles of 5°. Antennas are parabolic with typical diameters between 2.4 m and 3 m. The *G/T* of AHRPN stations will be 6.5 dB/K.

2.3.2.4 Low Rate Data (LRD)

The first NPOESS satellite, expected around 2013, will initiate the LRD application using a bandwidth of 6 MHz, replacing the current APT service provided by NOAA satellites. This service will operate in the 1 698-1 710 MHz frequency band.

2.3.3 Non-GSO MetSat Data Collection Systems (DCSs)

Data collection systems on non-GSO MetSat satellites provide a variety of information used principally by governmental agencies but also by commercial entities. Such data include a number of environmental parameters for oceans, rivers, lakes, land and atmosphere related to physical, chemical, and biological processes. It also includes animal tracking data. Use by commercial entities is limited, it comprises, for example, monitoring of oil pipeline conditions in order to protect the environment. Some transmitters are also deployed to report emergencies and supply data such as for hazard/disaster recognition. Examples of Data Collection Systems operated from non-geostationary meteorological satellites are ARGOS and Brazilian DCS. The Argos-2 system generation is currently flown only on the NOAA-15, -16, -17 and -18 polar-orbiting satellites. The third generation of Argos (Argos-3), already operational on Metop-A will be operated on NOAA-N', Metop-B and Metop-C, and also be embarked on a SARAL satellite.

The Argos system operates in the 401.580-401.690 MHz band, though thousands of platforms (known as platform transmitter terminals), each requiring only few kHz of bandwidth. Taking advantage of the nature of the orbits of polar-orbiting satellites, it is possible to accommodate many Argos platforms. The Argos-3 system generation introduces new data collection services offering high data rate (4 800 bit/s) and platform interrogation capability. The platform known as PMT (Platform Messaging Transceiver) is interrogated by satellites using the 460-470 MHz band.

For the fourth generation of the Argos system (Argos-4), it is expected that the system capacity and the bandwidth will have to be significantly increased.

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

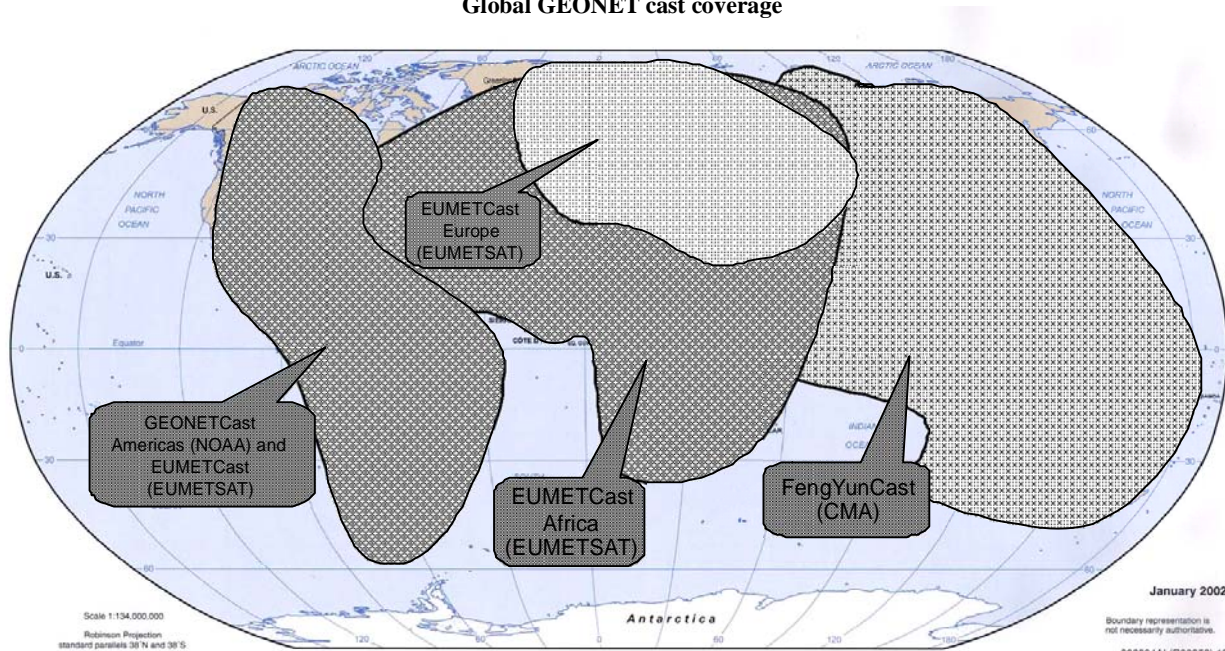
2.4 Alternative data dissemination mechanisms

Beside the traditional dissemination mechanisms of GSO and non-GSO MetSat systems an additional dissemination system is in the process of establishment, called GEONETCast (see Fig. 2-4), which is a major Global Earth Observation System of Systems (GEOSS) initiative to develop a worldwide, operational, end-to-end Earth observation data collection and dissemination system, using existing commercial telecommunications infrastructure. The GEONETCast concept is to use the multicast capability of a global network of communications satellites to transmit environmental satellite and in situ data and products from providers to users. The global coverage is planned to be provided through the integration of the FENGYUNCast system, the American GEONETCast component and the EUMETCast system.

For example, the EUMETCast system is EUMETSAT’s Broadcast System for Environmental Data, which is a multi-service dissemination system based on standard Digital Video Broadcast (DVB) technology. It uses commercial telecommunication geostationary satellites to multicast files (data and products) to a wide user community located within the geographical coverage zones of the commercial telecommunication satellites, which include Europe, Africa and the American continents.

Primarily used for the distribution of image data and derived products from Meteosat and Metop satellites, EUMETCast also provides access to data and services provided by several external data providers, e.g. national weather services and MetSat operators.

FIGURE 2-4
Global GEONET cast coverage



CHAPTER 3

METEOROLOGICAL AIDS SERVICE

		<i>Page</i>
3	Introduction.....	18
3.1	Allocated RF bands.....	18
3.2	Meteorological functions of the MetAids service.....	19
3.3	Examples of MetAids sensing systems.....	20
3.3.1	Radiosondes.....	20
3.3.2	Dropsondes.....	22
3.3.3	Rocketsondes.....	22
3.4	Factors influencing the characteristics of the MetAids systems.....	24
3.4.1	Ground-based receiver antenna system.....	24
3.4.2	Ground-based processing system.....	25
3.4.3	Expendable sensing packages.....	25
3.5	Characteristics of meteorological observations required from the MetAids service.....	26
3.6	Reasons for national variations in MetAids service operations.....	29
3.6.1	Variation in available technology.....	29
3.6.2	Differences in upper wind climatology.....	29
3.6.3	Differences in network density.....	30
3.6.4	Use of the 401-406 MHz band.....	30
3.6.5	Use of the 1 668.4-1 700 MHz band.....	30
3.6.6	Requirements for the retention of both bands.....	31
3.7	Future trends.....	31

3 Introduction

The meteorological aids (MetAids) service is defined in No. 1.50 of the Radio Regulations (RR) as a radio-communication 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 parameters and a remote base station. The *in situ* sensing system may be carried, for instance, by a weather balloon. Alternatively, it may be falling through the atmosphere on a parachute after deployment from an aircraft or meteorological rocket. The base station may be in a fixed location, or mounted on a mobile platform as used in defence operations. Base stations are carried on ships, and carried on hurricane watch or research aircraft.

3.1 Allocated RF bands

The frequency bands that are used for MetAids service (other than those governed by national footnotes) are shown in Table 3-1¹.

TABLE 3-1

Frequency bands used for MetAids systems/applications

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

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.

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

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 allocated in the RR because of national sharing agreements with other radiocommunication services, as noted earlier.

Routine radiosonde use in the band 27.5-28 MHz has ceased because of problems of interference from other services. Reviews of MetAids service use show commercially available radiosonde systems operating in the WMO network in the 400.15-406 MHz and 1 668.4-1 700 MHz frequency bands. The reasons for the continued use of these two MetAids service bands is discussed in a later section, once the systems in use have been discussed in more detail.

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

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

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

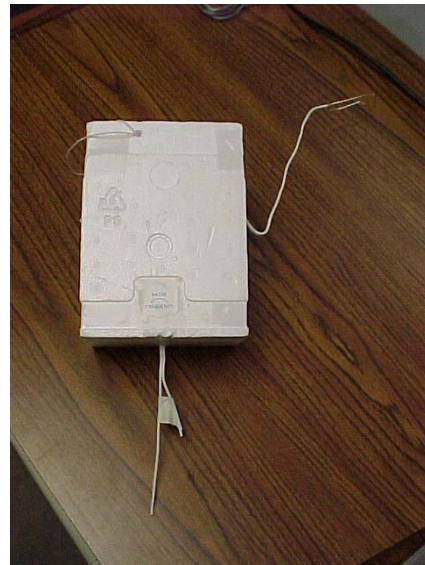
More than 800 000 radiosonde flights are carried out each year worldwide, see Figs. 3-1 and 3-2. In addition another 400 000 flights are made for various other applications. The base station sites used to launch the radiosondes are usually specially equipped so that the balloons can be launched in all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

FIGURE 3-1
A radiosonde flight train



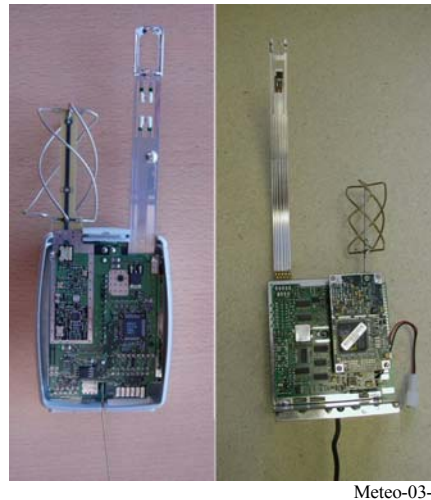
Meteo-03-1

FIGURE 3-2
Radiosondes



Meteo-03-2

FIGURE 3-3
Modern radiosonde electronics



Meteo-03-3

A typical radiosonde contains several major components: a transmitter, battery, sensor pack, and usually a navigational aids (NAVAID/GPS) receiver see Fig. 3-3. The transmitter transmits the data to the receiving station. 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 . 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.

Radiosonde systems that do not rely on NAVAID/GPS applications use radar tracking by suspending a reflector below the balloon. If the radiosonde relies on NAVAID/GPS signals for wind measurement, the radiosonde will also contain a NAVAID/GPS receiver for the type of signals used. Global positioning system (GPS), LORAN and VLF signals are used by NAVAID/GPS radiosondes.

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/GPS 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 NAVAID/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.

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 NAVAID/GPS 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-03-4

FIGURE 3-5
A rocketsonde



Meteo-03-5

3.4 Factors influencing the characteristics of the MetAids systems

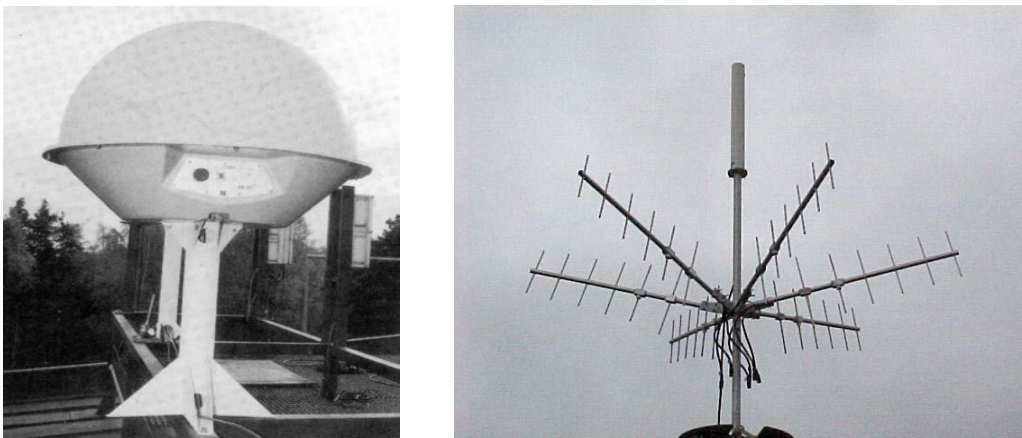
MetAids systems are comprised of several basic radiocommunication components. The ground portion of the system typically contains an antenna/receiver system and a signal processing system. Recommendation ITU-R RS.1165 – Technical characteristics and performance criteria for radiosonde systems in the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

3.4.1 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 1668.4-1700 MHz. Typically, the antenna/receiver system is ground based (for radiosondes and rocket-sondes), 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-03-6

Wind measurement is usually accomplished through RDF in the 1668.4-1700 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 1668.4-1700 MHz.

FIGURE 3-7
Tracking antenna systems (1 668.4-1 700 MHz)



Meteo-03-7

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 NAVAID/GPS for wind measurement also defer the processing of the NAVAID/GPS signal to the signal processing system as much as possible. Some MetAids simply receive the NAVAID/GPS 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) is now increasing as suitable devices able to operate over the extreme temperature ranges become more widely available.

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, paperboard or plastic package that is lightweight and easily destructible. The circuit cards are small and contain a small number of components and the circuitry is designed for maximum power efficiency. Due to the density and mass limitations, a large battery cannot be used to power the devices.

MetAids can be exposed to a variety of extreme conditions during flight. The temperature may range from 50° C to -90° C, humidity can range from very dry conditions to condensation 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.

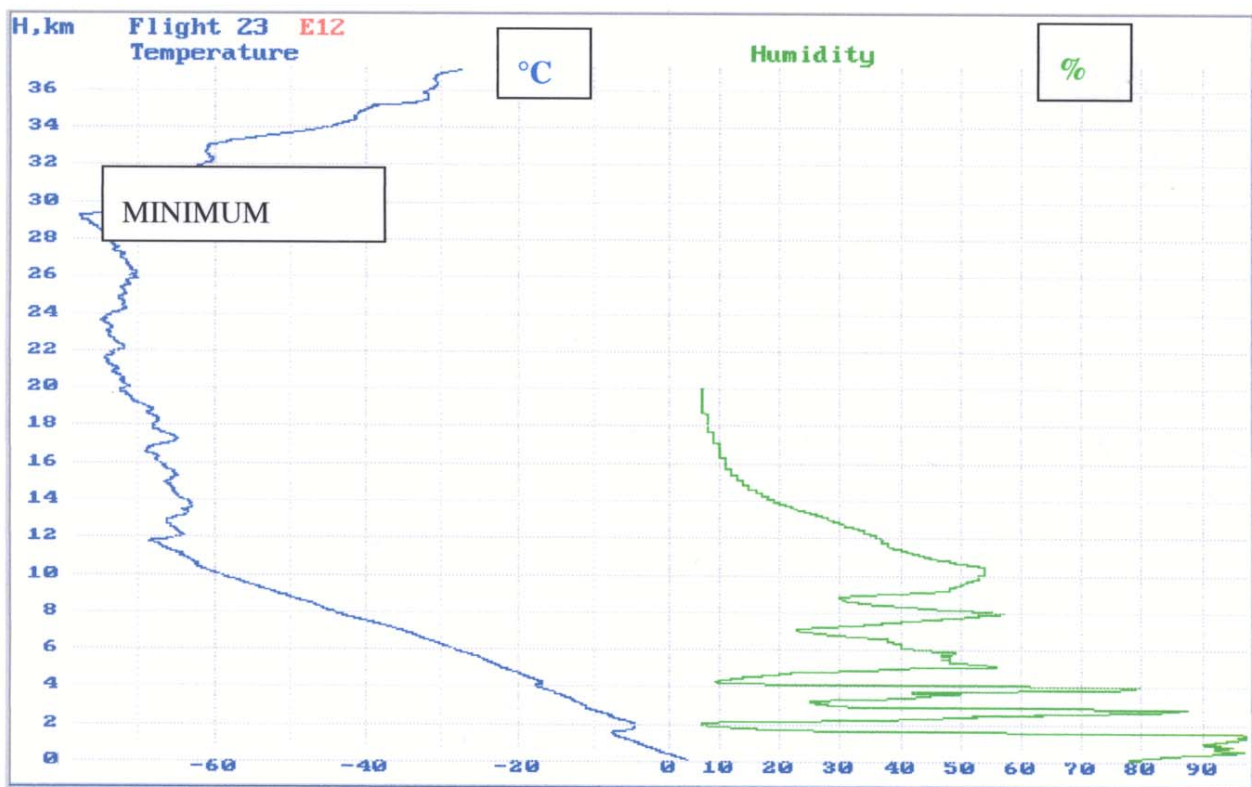
Figure 3-8 shows temperature and relative humidity measurements as a function of height, in a measurement from a climate monitoring site at 60° N in the UK (Lerwick, Shetland Islands, 23 January 2000). Radiosonde temperature measurements have small errors, less than 0.5° C at heights up to 28 km, and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

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 fulfill 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.

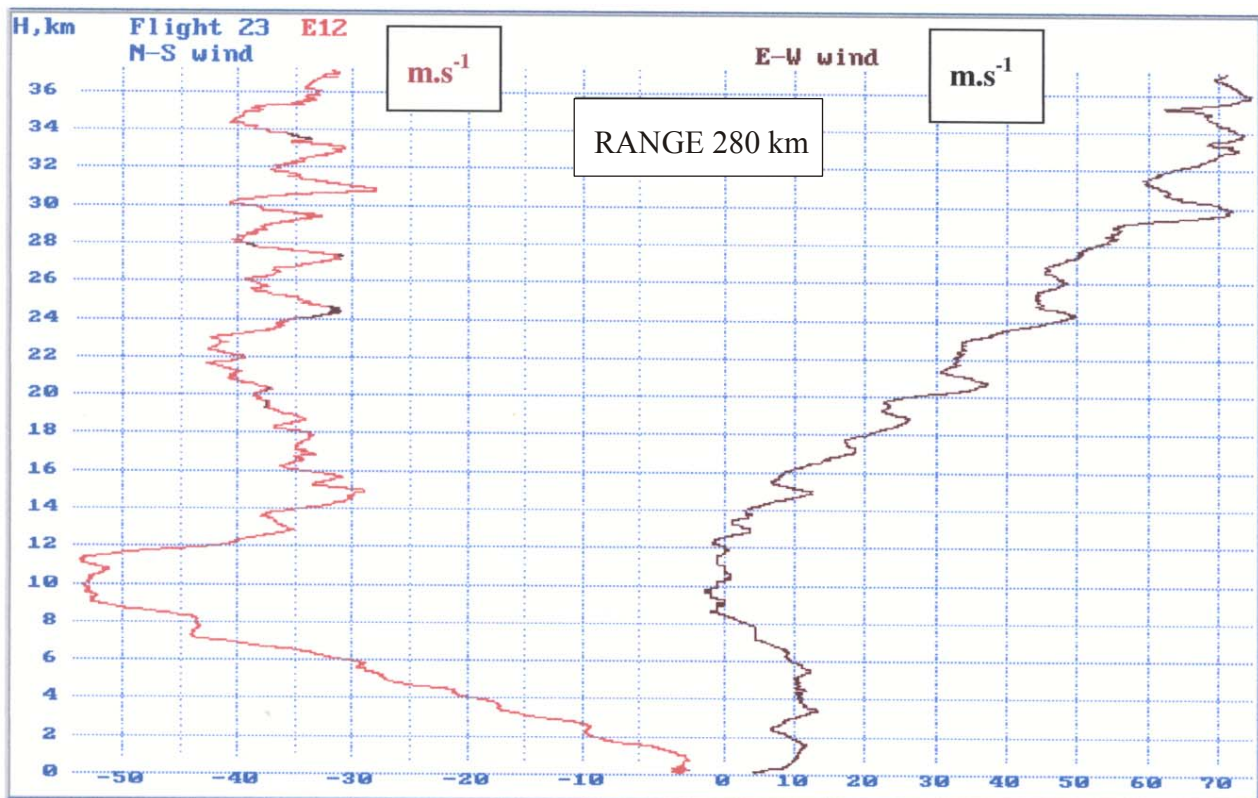
FIGURE 3-8
Temperature and humidity measurement by a radiosonde



Due to limitations in sensor technology, the humidity measurements terminate at height of 20 km. The minimum temperature in Fig. 3-8 occurred at about 29 km². The pronounced rise in the temperature above 29 km can be attributed to significant warming that takes place as a result of upper atmospheric motion during winters in the northern hemisphere.

Figure 3-9 shows wind measurements resulting from tracking the position of the same radiosonde flight (launched from Lerwick, Shetland Islands, 23 January 2000) as shown in Fig. 3-8. The movement of the radiosonde was computed using Loran-C navigation signals received by the radiosonde and then transmitted back to the base station. Accuracy is expected to be about 0.5 ms⁻¹ for each of the two orthogonal components shown at short range, decreasing to about 1.5 ms⁻¹ at the longest ranges, when the transmission back to the base station is less than optimal. In the N-S direction the strongest winds occurred between an altitude of 10 km and 12 km, with a jet stream centered 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



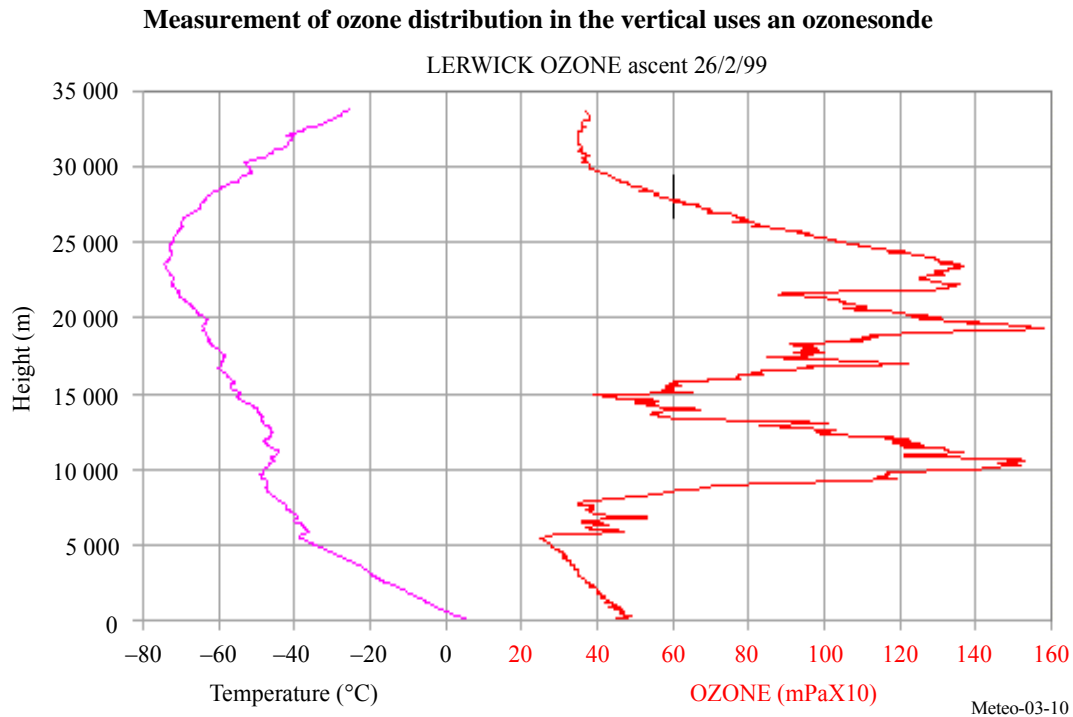
Meteo-03-9

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

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

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



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 5 years old, some of the national systems are still based on 30-40 year old technology. The measurements from these national systems are very important for all meteorologists, and adequate time must be allowed for these countries to introduce upgraded systems with more efficient use of the available radio frequency spectrum. It is hoped that this can be achieved by 2012.

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/GPS 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/GPS 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 WMO has defined and regularly reviews the minimum global and regional density requirements of MetAids networks. The spectrum requirements of the MetAids service vary on a country-by-country basis dependent upon the density of the network. Any estimate of spectrum requirements must be based on the whole user community for the service including defence and environmental agencies. Higher network density requires greater spectrum efficiency. The countries that operate the more dense networks usually have the budgetary resources to procure MetAids with more spectrum-efficient transmitters. These countries are usually the countries where there is also the greatest variation in atmospheric conditions from day-to-day. Countries that operate low-density networks may not have the resources to operate a large number of stations 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 where there are a limited number of launch stations. In such cases, the resources may be available to procure transmitters that can free some of the band for other uses. Australia is one case where the full band is not required and the administration has elected to use a portion of the band for other radio communication services. Therefore, spectrum may be available in some countries for other uses, but in a number of regions of the world, the entire band is required for MetAids operations. The WMO concluded that the entire 401-406 MHz band is required for MetAids operation for the foreseeable future and also accepted that standard radiosonde operations in the 400.15-401 MHz band would not be possible because co-channel sharing with satellite services is not feasible.

3.6.5 Use of the 1 688.4-1 700 MHz band

The situation in the 1 688.4-1 700 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 be kept in mind that only a portion of the band is usually available. Most countries can conduct operations in 7-8 MHz of spectrum, while there are a number of countries where upwards of 15 MHz is still required to support operations.

3.6.6 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-C) 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 operate their MetAids systems that are independent of international NAVAID/GPS systems as such, 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.

In addition, implementation of GPS on radiosondes for purposes of measuring winds is leading to significant improvements in the spectrum efficiency of NAVAID/GPS radiosondes. In most countries, it also allows 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/GPS 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.

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WMO Guide to meteorological instruments and methods of observation, No. 8.

CHAPTER 4

METEOROLOGICAL RADARS

		<i>Page</i>
4.1	Introduction.....	34
4.1.1	Meteorological radar types.....	34
4.1.2	Radar equation	35
4.2	Weather radars	36
4.2.1	User requirements	36
4.2.2	Weather radar networks	36
4.2.3	Operational aspects of reflectivity	38
4.2.4	Weather radars emission schemes and scanning strategies.....	39
4.2.4.1	Emission schemes	39
4.2.4.2	Noise calibration	40
4.2.4.3	Scanning strategies.....	41
4.2.4.4	Fixed echo elimination.....	41
4.2.5	Doppler radars.....	41
4.2.6	Dual-polarization radars.....	41
4.2.7	Conventional meteorological radar base data products.....	42
4.2.7.1	Base reflectivity	44
4.2.7.2	Mean radial velocity.....	44
4.2.7.3	Spectrum width	45
4.2.7.4	Dual polarization meteorological products	46
4.2.7.5	Derived data products	47
4.2.8	Present and future spectrum requirements	47
4.2.9	Vulnerabilities of weather radars	48
4.2.9.1	Types of possible interference	48
4.2.9.2	Impact of constant interference.....	48
4.2.9.3	Impact of pulsed interference.....	50
4.2.9.4	Interference from wind farms.....	51
4.2.10	Vulnerabilities of systems sharing spectrum with weather radars	54
4.3	Wind profiler radars (WPRs).....	54
4.3.1	User requirements	55
4.3.2	Operational and frequency aspects.....	56
4.3.3	Present and future spectrum requirements	57
4.3.4	Sharing aspects of wind profilers.....	58

4.1 Introduction

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

Meteorological radars are typically volume scanning, pencil beam radars which detect and measure both hydrometeor intensities and wind velocities. They are used to predict the formation of hurricanes, tornadoes and other severe weather events and to follow the course of storms on their destructive paths. Modern radars permit the track of path of large and small storms and provide information precipitation rates, which is used by forecasters in predicting the potential for flash floods. In addition, they provide relevant information on high winds and lightning potential.

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

4.1.1 Meteorological radar types

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

TABLE 4-1

Main weather radars frequency bands

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

Wind profiler radar (WPR) is a second type of meteorological radar. These radars provide data from a roughly cone-shaped volume which is directly above the radar. The WPR is a quite recent development and 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 typically located around 50 MHz, 400 MHz, 1 000 MHz and 1 300 MHz (see details in § 4.3).

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

All radars operate by emitting radio signals, which are reflected from a target such as vehicles, planes, raindrops or turbulence in the atmosphere. Although emitting powerful signals, the return signal of radars is weak. This is because the radiated signal must traverse the path twice, once from the radar to the target and again in the other direction. In the case of meteorological radars, this weakness is even exacerbated since the target (being either precipitations drops (rain, hail, snow,...) or even in case of Doppler mode, dust, insects or solely atmospheric disturbances) is not a particularly efficient reflector. The amount of signal returned is related to target reflectivity and can vary depending on the size and nature of the target. The need to receive these weak signals can be met variously by, e.g., higher transmitter powers, large antennas exhibiting high gain beamwidth product, extremely sensitive receivers, and long signal integration times. Relatively “quiet” spectrum – absence of man-made electronic noise and interference – is therefore a critical requirement.

4.1.2 Radar equation

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

$$\overline{P_r} = \frac{\pi^3 \cdot P_t \cdot G^2 \cdot \theta^2 \cdot c \cdot \tau \cdot |K|^2 \cdot L \cdot Z}{2^{10} \cdot \lambda^2 \cdot R^2 \cdot \ln 2} \quad (4-1)$$

where:

- $\overline{P_r}$: average return power (W)
- P_t : transmitter output power (W)
- G : antenna gain (dimensionless)
- K : complex index of refraction (dimensionless)
- λ : radar wavelength (m)
- c : speed of light (m/s)
- θ : antenna half power (3 dB) beamwidth (rad)
- τ : pulse width
- r : range to target
- L : loss factors associated with propagation and receiver detection (dB)
- Z : effective radar reflectivity (m³).

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

$$\overline{P_r} = \frac{\pi^3 c}{1024 \cdot \ln 2} \cdot \frac{P_t \cdot G^2 \cdot \theta^2 \cdot L}{\lambda^2} \cdot |K|^2 \frac{Z}{R^2} \quad (4-2)$$

\uparrow
 Constants

\uparrow
 Radar factors

\uparrow
 Target factors

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

- the target occupies the entire volume of the pulse
- the particles are spread throughout the contributing region
- the precipitation particles are homogeneous dielectric spheres with diameters small compared to the radar wavelength
- the size of the particles satisfies the Rayleigh Scattering condition
- the dielectric constant $|K|^2$ and the size distribution of the scatterers are homogeneous in the volume V considered
- the antenna pattern can be approximated by a Gaussian shape
- the incident and back-scattered waves are linearly polarized
- the effects of multiple scattering are neglected.

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

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

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

- received power P_r (W),
- range R (m),
- azimuth and elevation angles (degrees),
- excess propagation loss L_p (dB), and
- so-called radar constant C .

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

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

4.2 Weather radars

4.2.1 User requirements

Meteorologists use weather radar to, on the one hand, detect, locate, and measure the amount of precipitation within or falling from clouds and, on the other hand, to determine wind velocities using the movement of the precipitation or atmospheric particles. The radars measure the intensity of precipitation over specific time periods as well as the movement of precipitation or atmospheric particles toward or away from the weather radar antenna, enabling the measurement of rotation within meteorological events. This is a critical factor in detecting severe weather such as tornados or flash floods and in providing advance warning. The main user requirement for the weather radar is to detect solid and liquid precipitation and estimate the rate of precipitation and the radial velocity³.

4.2.2 Weather radar networks

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

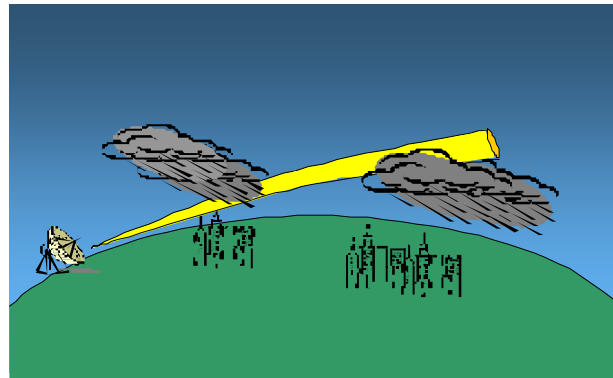
This results in a decrease in the percentage of the meteorological event that is illuminated by the beam. While the upper portion of the event can still be seen by the radar, its lower parts may no longer be visible. Precipitation that is taking place at some distance away from the radar may remain undetected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

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

³ This is the velocity of the precipitation either toward or away from the radar (in a radial direction). No information about the strength of the precipitation is given. Precipitation moving toward the radar has negative velocity. Precipitation moving away from the radar has positive velocity. Precipitation moving perpendicular to the radar beam (in a circle around the radar) will have a radial velocity of zero. The velocity is given in knots.

FIGURE 4-1

Synthetic description of radar beam height increase with distance



Meteo-04-1

FIGURE 4-2

Example of a weather radar network



Meteo-04-2

A complementary approach to overcoming this constraint is the deployment of small, low-cost, low-power, X-Band radars, which could supplement the data from existing weather radar networks. The (CASA²) is an example of such network, expected to dramatically improve sensing near the ground through a process called DCAS, distributive collaborative adaptive sensing. Within the DCAS process, data from multiple X-Band Radars will be assimilated in real-time for use in detection algorithms, numerical weather prediction and transportation models. Because of the distinct advantages of such a radar network, significant improvements are expected from the system in the analysis and prediction of surface weather conditions.

4.2.3 Operational aspects of reflectivity

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

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

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

For precipitation events where the raindrop size isn't known (or assumed), volume reflectivity can be related to the total liquid water volume per unit volume. The total volume of water in conjunction with the drop-size distribution and the corresponding terminal velocity of the drop facilitate the calculation of rainfall rate.

The radar reflectivity factor Z can be defined as:

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

where:

- Z : volume that is implied from the scatterer radar cross section of the total number of spheres in the volume
- D : water drop diameter
- V_e : effective drop volume.

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

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

where:

- Z : volume
- η : radar cross section per unit volume
- λ : incident wavelength
- $|K|$: complex index of refraction.

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

$$N(D) = N_0 \exp(-\Lambda D) \quad (4-7)$$

where:

- $N(D)$: number concentration of the diameter
- D : diameter
- ΛD : size interval
- N_0 and Λ : constants for a given meteorological event.

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

$$Z = \int_0^{\infty} D^6 N(D) dD \quad (4-8)$$

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

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

where:

- R : rainfall rate
- D^3 : raindrop volume that is proportional to Z
- $v_t(D)$: terminal velocity of a raindrop having a diameter D
- ρ : density of water.

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

$$Z = AR^b \quad (4-10)$$

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

4.2.4 Weather radars emission schemes and scanning strategies

4.2.4.1 Emission schemes

To ensure volume scan processing, in so-called “scanning strategies” (typically in a range of 10-15 min), meteorological radars make use of a variety of different emission schemes at different elevations, using sets of different pulse width, PRF’s and rotation speeds. There are no typical schemes, these schemes varying based on a number of factors such as the radar capabilities, the radar environment and the required meteorological products.

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

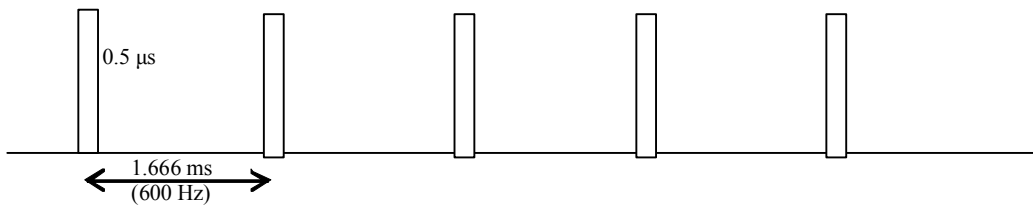
- Operational elevation ranging from 0° to 90°
- Pulse width ranging from 0.5 to 2.5 μs (for operational radars)
- Pulse repetition Frequency (PRF) ranging from 250 to 1 200 Hz
- Rotation speed ranging from 1 to 6 rpm
- Use given radars of different emission schemes which mix different pulse widths and PRF’s, and in particular the use of fixed, staggered or interleaved PRF (i.e. different PRF during a single scheme).

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

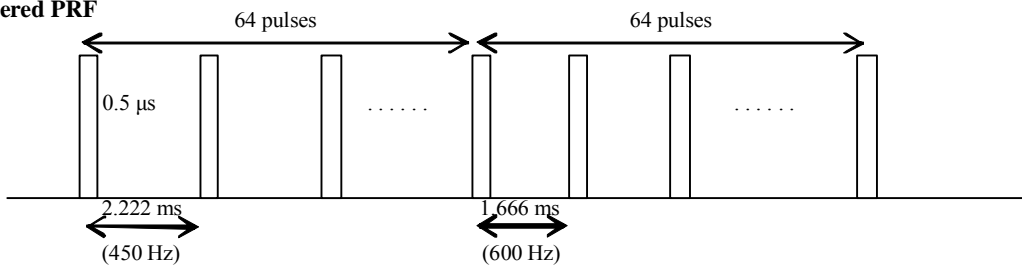
FIGURE 4-3

Some types of weather radar emission schemes

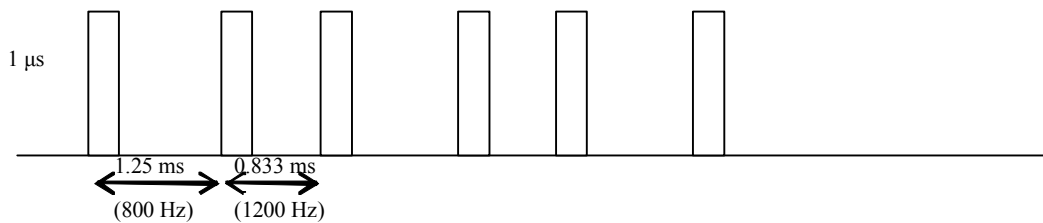
Fixed PRF



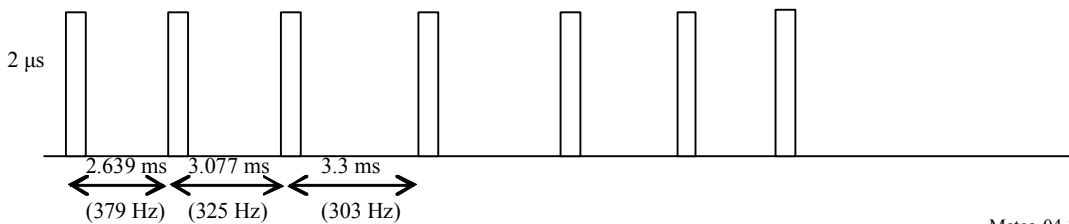
Staggered PRF



Double interleaved PRF (double PRT)



Triple interleaved PRF (triple PRT)



Meteo-04-3

4.2.4.2 Noise calibration

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

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

- 1 for each gate, the radar measures the return signal corresponding to the useful signal (S) and the noise (N), i.e. $N + S$
- 2 To get the S , the radar extract from $N + S$, the noise level N

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

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

This noise calibration, also called “**Zero check**”, is therefore performed on a regular basis, either during regular radar emissions (by estimation) or during specific measurement periods of time (see the example scanning strategy below).

It should be noted that, for a number of radars, this noise measurement is performed without any radar emission, hence meaning that it could have an impact on the design of certain radio systems that aim at detecting radar signal to mitigate interference or, should any interference occurs during such calibration, that it could impact the whole radar measurements following this calibration, likely the whole scanning strategy. In particular, this interference would more than likely lead to presenting lower precipitation rates than the real situation, with obvious consequences on operational and alert processes.

4.2.4.3 Scanning strategies

The different emission schemes depicted above are used on a number of radar in their scanning strategy, during which, at different elevations and rotation speeds, one emission scheme is transmitted. Here also, there is no typical scanning strategy, these strategies varying depending on a number of parameters, including basic meteorological requirements, environment of the radar, specific meteorological conditions, etc.

An example of such scanning strategy is given on Figs. 4-4 and 4-5.

4.2.4.4 Fixed echo elimination

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

- Doppler filtering uses a high pass filter to reduce the ground clutter. That process is efficient if the radial wind velocity is above the cut-off frequency of the Doppler filter.
- Statistical filtering based on the fact that the variance of rain is higher than the variance of ground clutter reflectivity. The statistical filtering process is efficient even when the rain radial velocity is null (tangential rain).
- The use of polarimetric radar for rain and ground clutter discrimination.

4.2.5 Doppler radars

Doppler weather radars have been used for more than 30 years in atmospheric research to measure convection within thunderstorms and to detect gust fronts and are now widely used for operational weather radar systems. Unlike earlier radars, Doppler equipment is capable not only of determining the existence and position of reflective targets but also their radial velocity. This permits the measurement of wind speed, detection of tornadoes, and the measurement of a wind field using velocity azimuth display scanning.

Ground clutter suppression is an important capability. New developments in this area are focused on coherent transmitters such as klystrons or traveling 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.

4.2.6 Dual-polarization radars

Polarimetric or dual-polarization radar technology permits the identification of scatterers by remotely sensing their shapes. Polarimetric weather radar can be used to improve hydrometeor identification and the reliability and accuracy of precipitation rates which are needed for hydrological applications. In fact, falling raindrops tend to flatten (obsolete spheres), the flatness increasing with drop size in the horizontal direction.

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 $\phi_h - \phi_v$, taking into the account the differential attenuation as well, are considered very promising for yielding accurate assessments of rainfall.

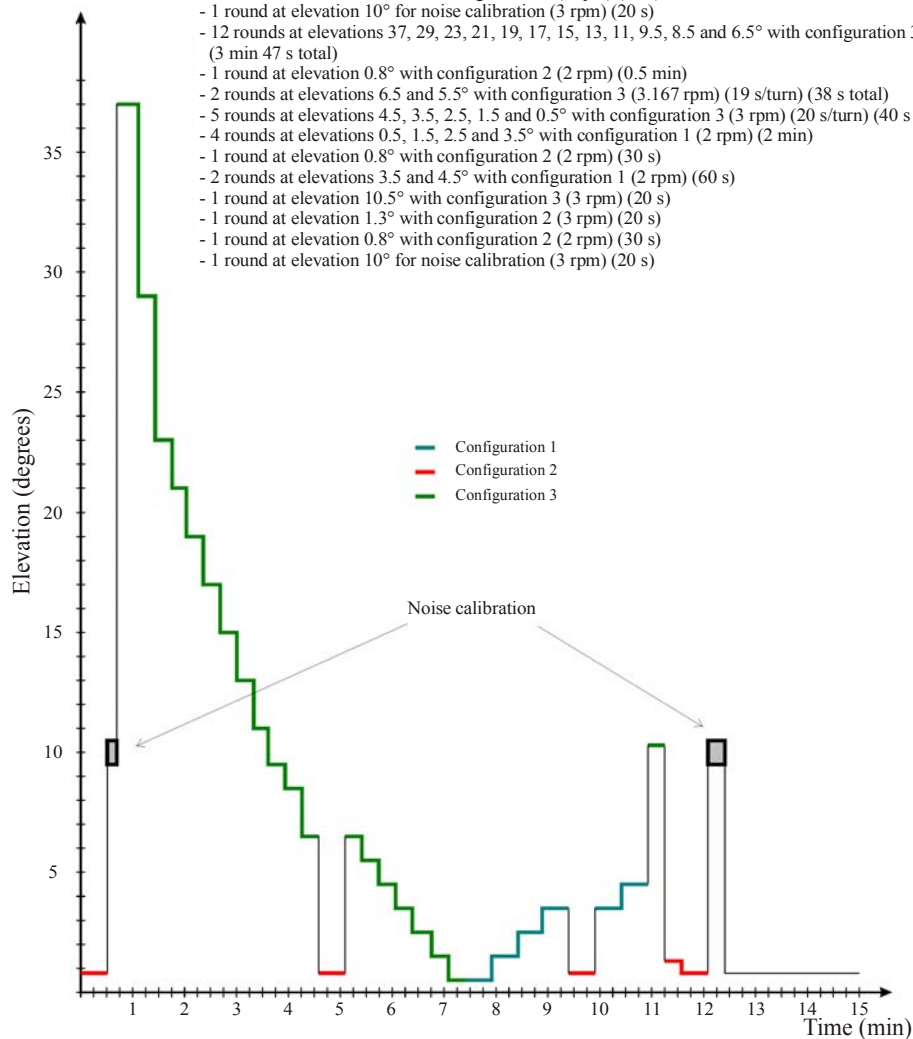
In addition to their shape, the hydrometeors are characterized by their dielectric constants, a primary factor in computing scattering and attenuation cross sections. Dielectric properties of hydrometeors vary with radar frequency, where liquid water and ice differ significantly. Taking advantage of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

FIGURE 4-4

Description of a weather radar scanning strategy

Typical scan strategy (total time around 15 min):

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

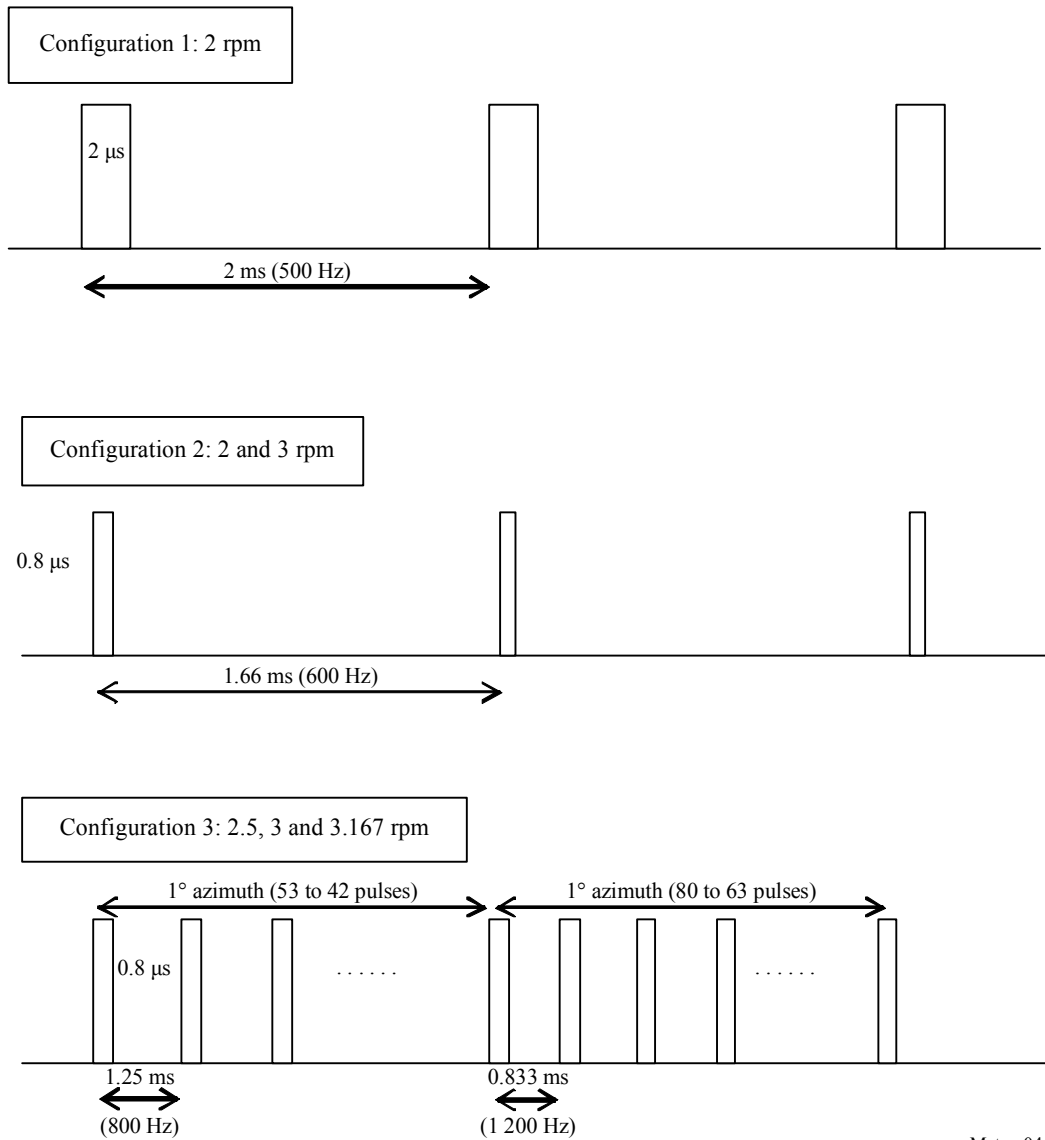


Meteo-04-4

4.2.7 Conventional meteorological radar base data products

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

FIGURE 4-5
Emission schemes associated with scanning strategy as in Fig. 4-4



Meteo-04-5

TABLE 4-2

Representative met radar base data accuracy requirements

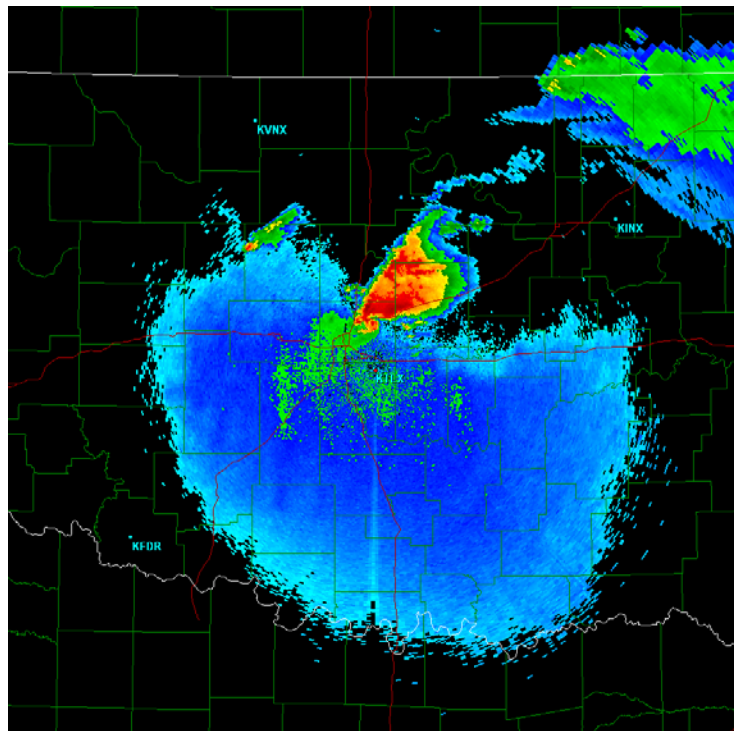
Base data product	Design accuracy requirement
Base reflectivity	< 1 dB
Mean radial velocity	< 1 m/s
Spectrum width	< 1 m/s

4.2.7.1 Base reflectivity

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

FIGURE 4-6

Typical reflectivity representation

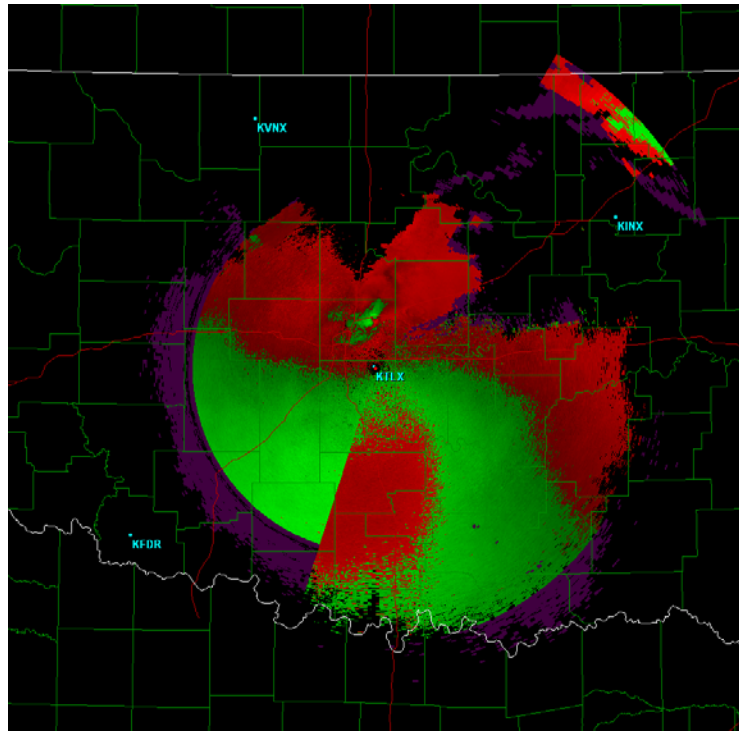


Metco-04-6

4.2.7.2 Mean radial velocity

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

FIGURE 4-7
Typical radial velocity representation

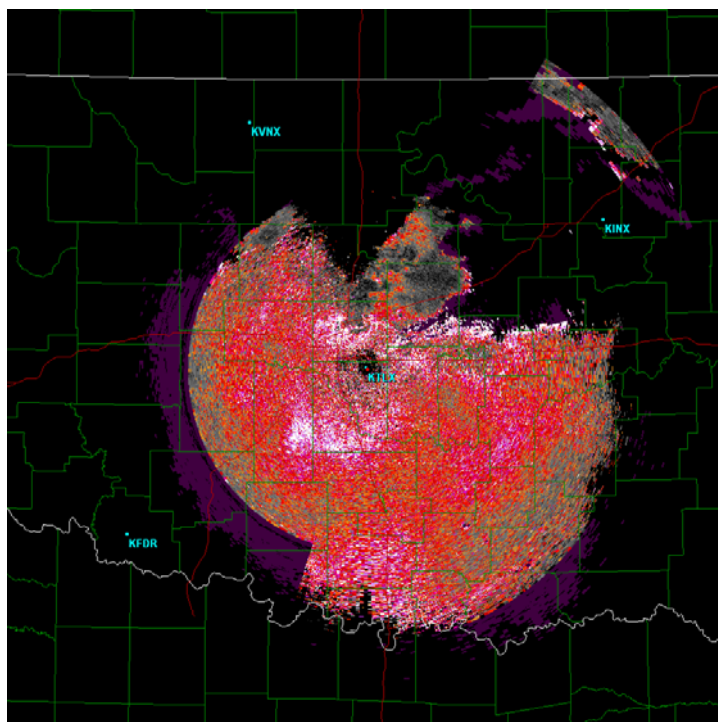


Meteo-04-7

4.2.7.3 Spectrum width

In met radar design, spectrum width is calculated from the single lag correlation assuming a Gaussian spectral density. It is a measure of the dispersion of velocities within the radar sample volume and is the standard deviation of the velocity spectrum. Spectral width depends on reflectivity and velocity gradients across the pulse volume and turbulence within the pulse volume [Doviak and Zrníc 1984]. There is no averaging of samples used in spectrum width calculations. There is however an accumulation of the real and imaginary parts of the sample series, i.e. the samples taken over the radial.

FIGURE 4-8
 Typical spectrum width representation



Meteo-04-8

4.2.7.4 Dual polarization meteorological radar products

4.2.7.4.1 Differential reflectivity

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

4.2.7.4.2 Correlation coefficient

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

4.2.7.4.3 Linear depolarization ratio

Another polarimetric radar product is linear depolarization ratio which is a ratio of a vertical power return from a horizontal pulse or a horizontal power return from a vertical pulse. It, too, is a good indicator of regions where mixtures of precipitation types occur.

4.2.7.4.4 Specific differential phase

The specific differential phase is also a polarimetric meteorological radar product. It is a comparison of the returned phase difference between the horizontal and vertical pulses. This phase difference is caused by the difference in the number of wave cycles (or wavelengths) along the propagation path for horizontal and vertically polarized waves. It should not be confused with the Doppler frequency shift, which is caused by the motion of the cloud and precipitation particles. Unlike the differential reflectivity, correlation coefficient and linear depolarization ratio, which are all dependent on reflected power, the specific differential phase is a “propagation effect”. It is also a very good estimator of rain rate.

4.2.7.5 Derived data products

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

4.2.8 Present and future spectrum requirements

As for a number of radio applications, the choice of the frequency band (or wavelength λ) mainly results from a trade-off between the range/reflectivity, which varies as λ^{-4} , the rain attenuation, which decreases as λ increases to become negligible at decimetric wavelengths, data accuracy and cost. For example, the Ka band (around 35 GHz, 8.6 mm wavelength) is well suited for detecting small water drops, which occur in non-precipitating clouds ($\leq 200 \mu\text{m}$) whereas, on the other hand, the S band (2 700-2 900 MHz, 10 cm wavelength) is chosen for detecting heavy rain at very long ranges (up to 300 km) in tropical and temperate climates.

The C band (5 600-5 650 MHz, 5.4 cm wavelength) is in general preferred for use in temperate climates since it represents a relevant compromise between the above-mentioned parameters, allowing rain detection at long ranges (up to 200 km) although its quantification would be in fact limited above 100 km and offering the advantage of lower cost resulting from both lower power and smaller antenna size compared to lower-frequency radars having the same spatial resolution.

X band (9 300-9 500 MHz, 2.5-3.2 cm wavelength) weather radars are more sensitive and can detect smaller particles but, since experiencing higher attenuation, are used for only very short range weather observation (about 50 km). These radars are used for studies on cloud development because they can detect the tiny water particles and are also used to detect light precipitation such as snow. In addition, due to their small size, X Band Weather Radars are often used as mobile portable units. 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 range⁴ 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, a constant given by:

$$R_m \cdot V_m = c \frac{\lambda}{8} \quad (4-11)$$

where:

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

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

c : speed of light (3×10^8 m/s)

λ : radar signal wavelength.

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

⁴ The maximum unambiguous range is the longest range to which a transmitted pulse can travel and return to the radar before the next pulse is transmitted. In other words, the maximum unambiguous range is the maximum distance that radar energy can travel round trip between pulses and still produce reliable information.

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.

4.2.9 Vulnerabilities of weather radars

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

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

It must also be 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.

4.2.9.1 Types of possible interference

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

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

Radar protection criteria levels for meteorological radars can be found in relevant ITU-R Recommendations, and in particular a maximum $I/N = -10$ dB for constant interference.

4.2.9.2 Impact of constant interference

4.2.9.2.1 Geographical coverage

Constant interference can decrease the range of the radar resulting in limiting the geographical area of coverage due to the corresponding noise increase. Current coverage of meteorological radars roughly extends up to 200 km. Table 4-3 summarizes the losses in range and coverage as interference (noise) increases.

4.2.9.2.2 Rain rate

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

TABLE 4-3

Loss in range and coverage

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

TABLE 4-4

Precipitation rate increase

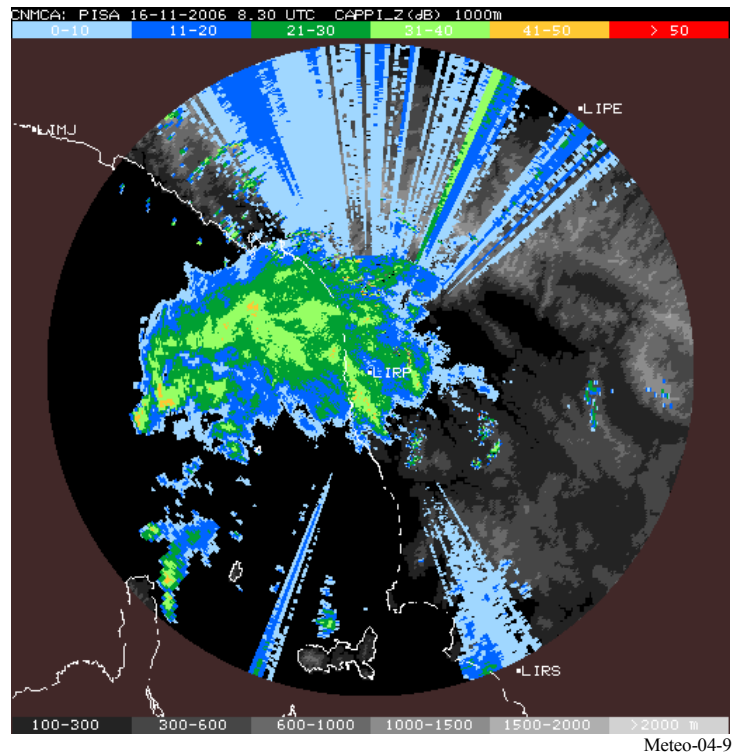
Noise increase (dB)	Corresponding I/N (dB)	Stratoform rate increase (%)	Convection rate increase (%)	Snow rate increase (%)	Hail rate increase (%)
0.5	-10	7.5	8.0	5.9	9.3
1	-6	15.5	16.6	12.2	19.5
2	-2.3	33.4	35.9	25.9	42.9
3	0	54.0	58.5	41.3	70.8
4	1.8	77.8	84.8	58.5	104.2
5	3.3	105.4	115.4	77.8	144.1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

It is worth noting that an increase in interference would not modify the radars ability to detect rain cells (i.e. a measurement not considered as a rain cell will still not be considered as such) but would only have an impact on the rain rate.

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

An example of impact of a constant interference on a radar precipitation mode can be seen in Fig. 4-9. It is important to highlight that, although being a constant interference, the variation in impact is due to the rotation of the antenna, the maximum interference (in green on this picture) being produced in the azimuth of the interfering source.

FIGURE 4-9

Example of interference to precipitation mode of a weather radar**4.2.9.2.3 Wind measurement**

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

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

- *Case 1* – If the phase of the interfering signal detected by the radar is random, it means that the resulting vector would be statistically null; whatever would be its level. Hence, it would theoretically not have any impact on the wind measurements.
- *Case 2* – On the contrary, if the detected phase is not random and almost constant, it would result in a constant vector with a certain module and the impact on the wind measurement will depend on both the phase and module of such vector. However, the determination of such impact, even for a constant interference level is likely not to be easy and is hence not made at this point.

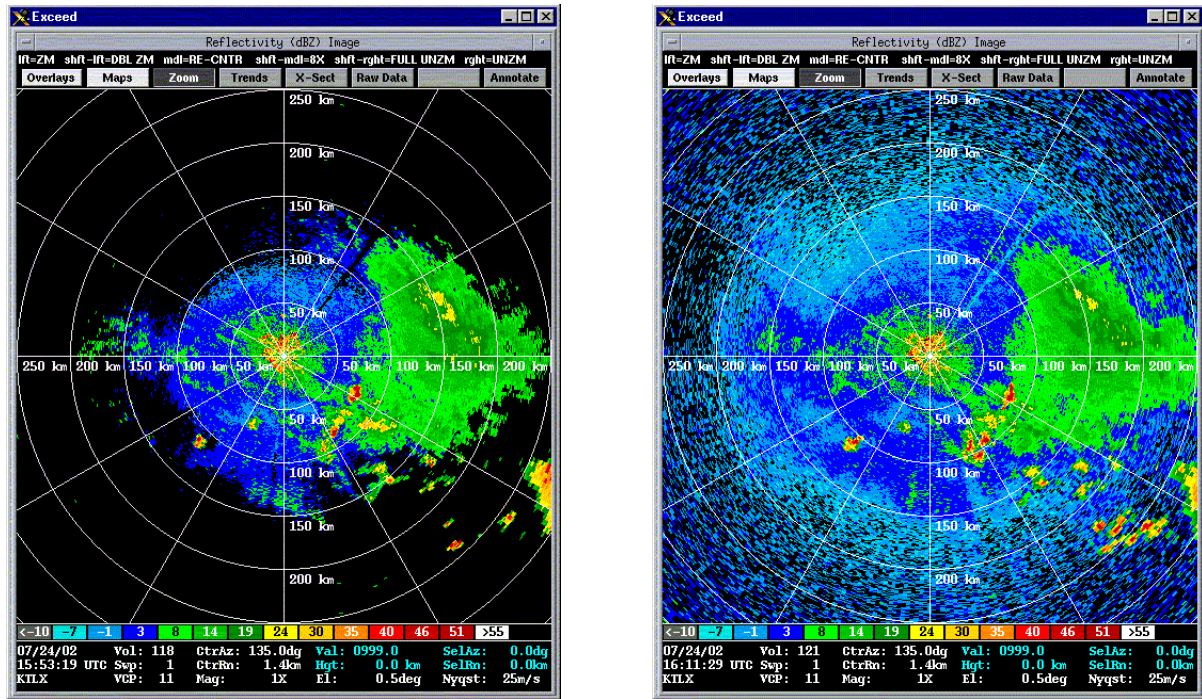
In addition, one can also assume that when the level of interference is much lower than the wanted signal, the phase of this latter is not modified whereas, on the contrary, if the interfering signal is much higher, then the phase detected by the radar will be the phase of the interfering signal. In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

4.2.9.3 Impact of pulsed interference

Pulsed interference can have a significant impact on the reflectivity data that a meteorologist uses to forecast severe weather events. In some cases pulsed interference could result in a returned data that cannot reliably produce an image of targets in the atmosphere. An example of this can be seen in Fig. 4-10.

FIGURE 4-10

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



Interference free

Interference corrupted

Meteo-04-10

4.2.9.4 Interference from wind farms

In recent years, increasingly larger wind turbines are being constructed due in part to generator efficiencies, desire to tap stronger, higher-level wind fields, generator efficiencies, etc. Of course, the economic incentive is the main driving force and careful analysis has provided the impetus for larger wind turbine designs. A typical turbine structure consists of a tower, nacelle, rotor, and three blades. A typical generation facility, or wind farm, is made up many wind turbine generators. Wind turbines and farms, even at quite large distances, present a high potential to degrade meteorological data over very large areas and could have a non-negligible impact on weather nowcasting and forecasts.

For accurate weather forecasting, weather radars are designed to look at a relatively narrow altitude band. Due to the sensitivity of the radars, wind turbines, if deployed with line of site of a weather radar facility, have the potential to significantly reduce the weather radar performance. There are three mechanisms through which the performance can be degraded; masking, clutter and backscatter.

4.2.9.4.1 Masking

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

4.2.9.4.2 Clutter

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

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

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

4.2.9.4.3 Backscattered energy from turbulent eddies

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

4.2.9.4.4 Examples of wind turbine clutter

Two distinct examples of interference from Wind Farms⁵ are provided in Fig. 4-11 [Palmer and Isom, 2006]. As expected, the reflectivity shows large values near 45 dBZ with sporadically large spectrum widths of over 10 m/s. The relatively small region of high reflectivity to the south-west of the radar is clearly visible and matches the location of a wind farm that is approximately 45 km from the weather radars location.

FIGURE 4-11

Examples of Wind Farm interference to weather radar under clear-sky conditions

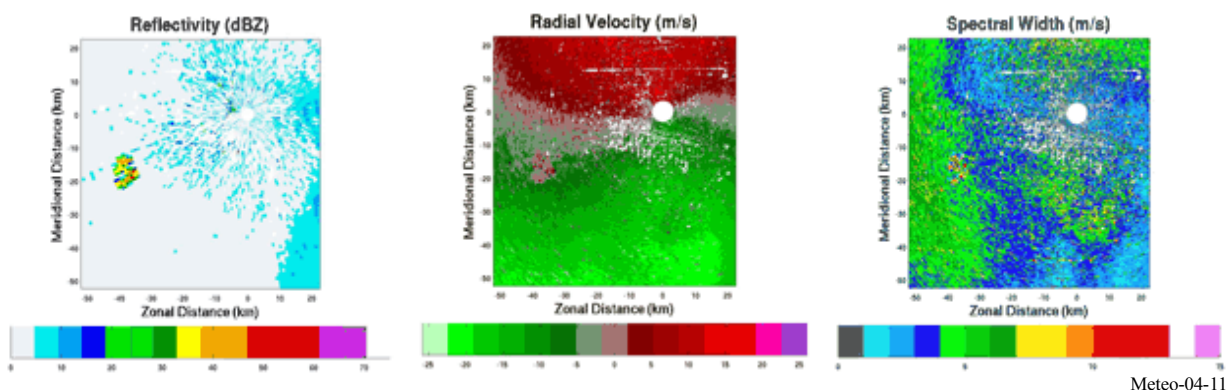
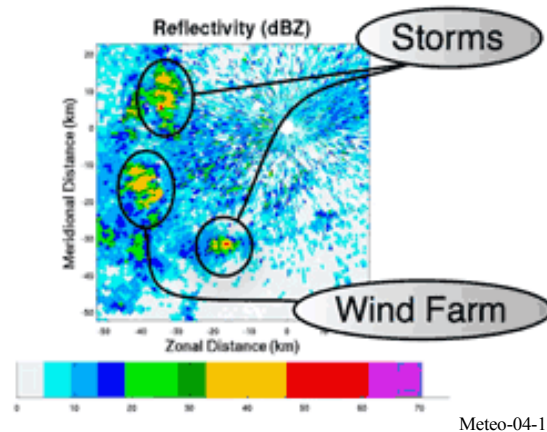


Figure 4-12 shows the same wind farm during a thunderstorm event.

⁵ Wind Farms are clusters of wind turbines that are used to generate power.

FIGURE 4-12

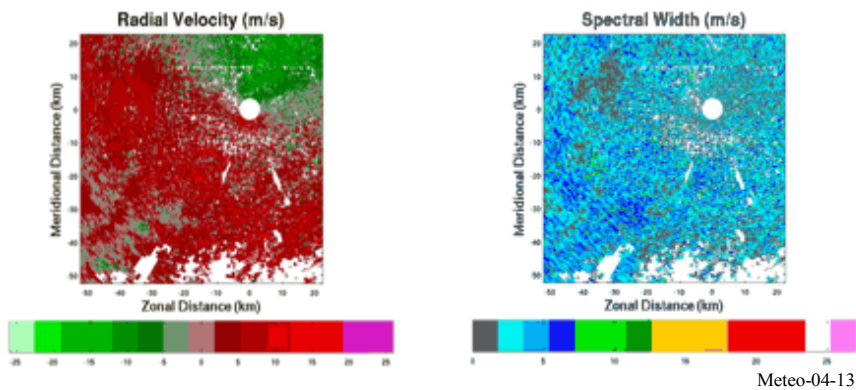
Example of interference from a Wind Farm and its impact upon reflectivity during an isolated thunderstorm incident



Without prior knowledge, it would be extremely difficult to distinguish between the WTC and the thunderstorms. Since the blades rotate toward and away from the radar, one would expect a near-zero mean Doppler velocity. Of course, the large spectrum widths will reduce the accuracy of the Doppler velocity estimates as illustrated in Fig. 4-13 by small deviations from zero.

FIGURE 4-13

Examples of Doppler velocity data estimates during a thunderstorm event



4.2.9.4.5 Impact of WTC on meteorological radar operations and forecasting accuracy

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

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

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

Some form of WTC mitigation will be required in order to protect meteorological radars from harmful interference from wind turbine farms. Before any final conclusions can be made regarding processing methods to mitigate WTC, additional studies of WTC should be conducted in order to understand the full

extent and the impact of WTC on the meteorological radars. Once this has been defined, methods to mitigate WTC may need to be developed given the expected growth of wind-power based generation systems.

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

- 1 that no wind turbine should be deployed at a range from radar antenna lower than:
 - 5 km for C-band radars
 - 10 km for S-band radars
- 2 that projects of wind parks should be submitted to an impact study when they concern ranges lower than:
 - 20 km for C-band radars
 - 30 km for S-band radars.

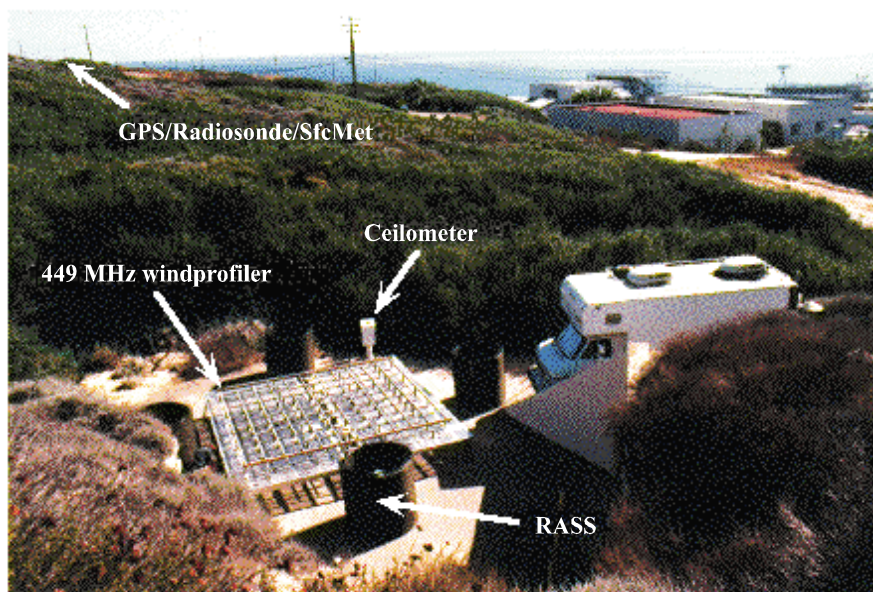
4.2.10 Vulnerabilities of systems sharing spectrum with weather radars

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

4.3 Wind profiler radars (WPRs)

Wind Profiler Radars are used to obtain the vertical profiles of the wind over an unattended and sometimes remote area by detecting the tiny fraction of emitted power backscattered from turbulence in the clear atmosphere. Figure 4-14 is a photograph of a typical wind profiler radar installation.

FIGURE 4-14
Photo of wind profiler installation



Metco-04-14

One of the major advantages of wind profilers to other wind measurement systems is their ability to continuously monitor the wind field. In addition, they can also be used to detect precipitation, measure major disturbances in the vertical velocity field (gravity waves and convective updrafts), measure the intensity turbulence and measure atmospheric stability. They can also provide detailed information on atmospheric virtual temperature through the addition of a Radio Acoustic Sounding System (RASS)⁶.

4.3.1 User requirements

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

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

where:

- \bar{P}_t : average transmitted power (W)
- A_e : effective aperture (degrees)
- Δ_z : height resolution (m)
- z : height (m)
- λ : wavelength (m)
- t_{obs} : observation (averaging) time (s)
- T_{sys} : system noise temperature (K)
- C_n^2 : structure parameter (dimensionless).

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

⁶ RASS utilizes an acoustic source that is matched in frequency so that the wavelength of the acoustic wave is matched to half the wavelength of the radar transmitted electromagnetic wave. RASS measures the speed of the acoustic wave which is dependent upon temperature. In this way RASS provides a remote measurement of the atmospheric virtual temperature.

- 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.

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 (4-13):

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

Because of interference and congestion in the radio-frequency spectrum and its consequent regulation, wind profiler radar frequencies cannot be freely chosen. Some demanding applications, such as the MU radar in Japan and those at the Eastern and Western Launch Ranges in the United States of America, have resulted in the use of very large (about 10 000 m²), powerful (250 kW or more peak, 12.5 kW or more average), short pulse (1 μs) radars operating near 50 MHz. Researchers have also operated other profilers on a non-interference basis at frequencies between 40 and 70 MHz.

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

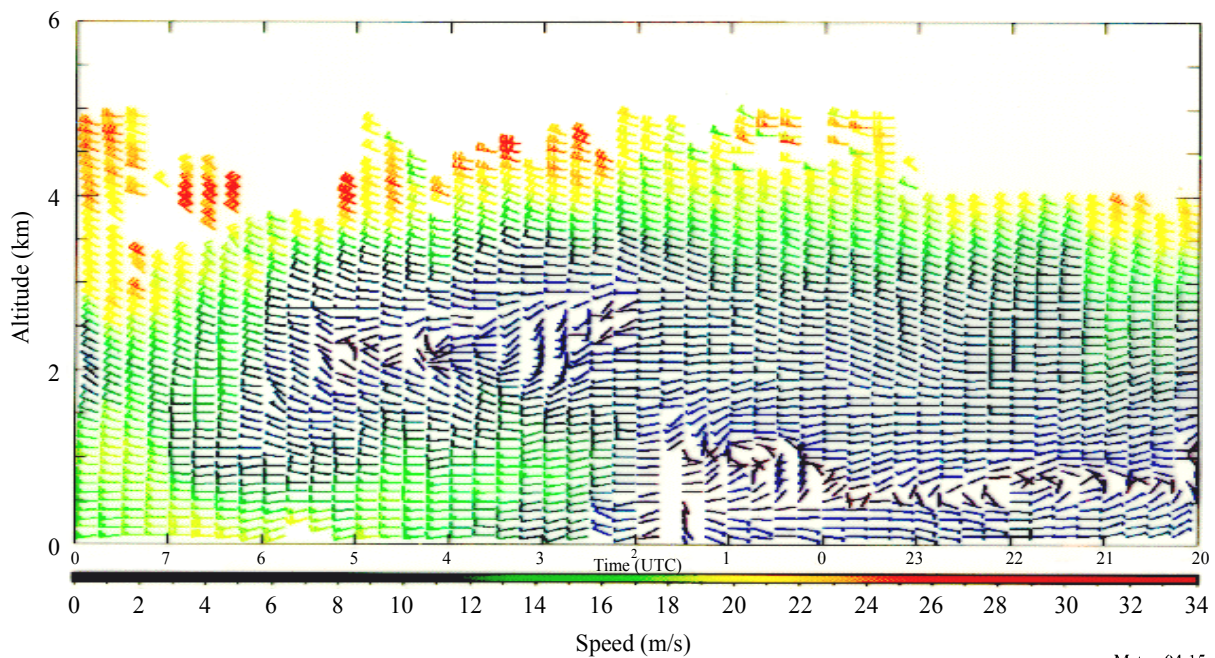
- measure wind profiles from about 0.5-16 km above the radar with vertical resolutions of 250 m at low altitudes and 1 000 m at high altitudes using antennas with about 32 dBi gain;
- mean powers of about 500 W and 2 000 W when probing low and high altitudes, respectively;
- while operating with necessary 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.

Increasing the operational frequency of a wind profile radar provides a higher degree of measurement resolution at the cost of lowering the overall height measurements. As such, profilers operating at 915 MHz and 1 270-1 375 MHz are typically regarded as boundary layer profilers, capable of measuring the wind profile in only the lowest few kilometres of the atmosphere. These perform with vertical resolution of about 100 m using antennas with gains below 30 dBi and mean powers of about 50 W while operating with necessary bandwidths of 8 MHz or more.

As an example mobile profiling system operating at 924 MHz produced the plot of wind velocity vs. altitude (see Fig. 4-15). 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.

FIGURE 4-15
Wind velocity vs. altitude



Meteo-04-15

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. Under these rationales, profilers tend to be compatible with most ground-based services.

It is generally agreed that 2 to 3 MHz of bandwidth are required near 400 MHz and 8 to 10 MHz near 1 000 MHz or 1 300 MHz and it can be assumed that provisions of Resolution 217 (WRC-97), as below, are sufficient to fulfill these requirements:

“... to urge administrations to implement wind profiler radars as radiolocation service systems in the following bands, having due regard to the potential for incompatibility with other services and assignments

to stations in these services, thereby taking due account of the principle of geographical separation, in particular with regard to neighbouring countries, and keeping in mind the category of service of each of these services:

- 46-68 MHz in accordance with No. 5.162A
- 440-450 MHz
- 470-494 MHz in accordance with No. 5.291A
- 904-928 MHz in Region 2 only
- 1 270-1 295 MHz
- 1 300-1 375 MHz;”

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

4.3.4 Sharing aspects of wind profilers

The bands for profiler use allocated by WRC-97 were carefully selected to minimize the likelihood of interference to and from other users of these bands. Before the identification of bands for wind profiler radars an experimental network was developed in the band 400.15-406 MHz. Operational experience showed operation of wind profiler radars in 400.15-406 MHz caused interference to COSPAS-SARSAT.

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

- –18 dB(W/kHz) at the centre frequency (449 MHz)
- –36 dB(W/kHz) 0.5 MHz away
- –55 dB(W/kHz) 1 MHz away
- –70 dB(W/kHz) 2 MHz away
- –79 dB(W/kHz) 4 MHz away.

These low values, when combined with low antenna heights and path losses proportional to $1/r^4$ for propagation over the surface of the Earth, result in making geographical separation a very effective sharing tool. 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. Subsequent efforts to alleviate the problem with the wind profilers in the band 400.15-406 MHz showed that the modulation used by 404 MHz WPRs has a significant impact upon their sharing characteristics. Currently, the pulses are phase-coded to distinguish the two or three “chips” within each pulse so as to 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.)

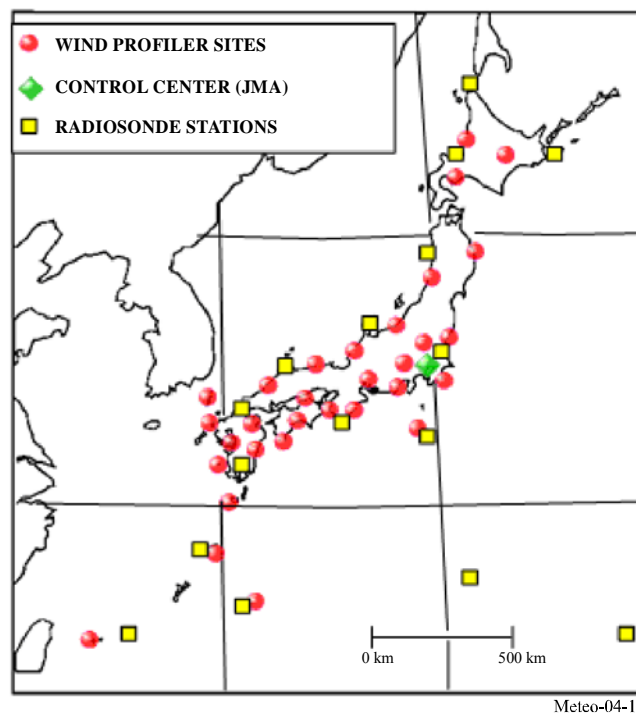
The phase coding applied to 404 MHz profiler emissions must be “undone” in the receiver. As a result, interference from other, non-WPR systems appears incoherent and noise-like to the profiler. Hence, the minimum detectable (profiler) signal is about -170 dBm, while interference is troublesome only at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

Resolution 217 (WRC-97) identifies 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.

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

The Japan Meteorological Agency (JMA) is operating a Wind Profiler Network and Data Acquisition System (WINDAS) network for the purpose of monitoring the development of and predicting severe weather events. The network consists of thirty-one 1.3 GHz wind profilers installed across Japan that communicate with a control center which is located at the JMA headquarters in Tokyo (Fig. 4-16).

FIGURE 4-16
An example of a wind profiler radar network



The data from this system has been used as initial values in all the JMA Numerical Weather Prediction models since June of 2001. to aid in the prediction of sever weather events. The data is combined with data from Doppler radars and commercial aircraft to provide a comprehensive “Upper-air wind analysis”. This analysis is then distributed throughout the world, via the Global Telecommunication System and can also be found on the JMA Web site (<http://www.jma.go.jp/jp/windpro/>).

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CHAPTER 5

PASSIVE AND ACTIVE SPACEBORNE REMOTE SENSING FOR METEOROLOGICAL ACTIVITIES

		<i>Page</i>
5	Introduction.....	62
5.1	Passive microwave radiometry sensing	63
5.1.1	Spectrum requirements	64
5.1.2	Observation of Earth's surface features	66
5.1.2.1	Observation over ocean surfaces.....	66
5.1.2.2	Observation over land surfaces	67
5.1.2.3	Auxiliary parameters for other remote sensing instruments	68
5.1.3	Performance parameters.....	68
5.1.3.1	Radiometric sensitivity	68
5.1.3.2	Radiometer threshold ΔP	69
5.1.3.3	Geometric resolution.....	69
5.1.3.4	Integration time	69
5.1.4	Typical operating conditions of passive sensors	69
5.1.4.1	Low Earth-orbiting satellites.....	69
5.1.4.2	Geostationary satellites	69
5.1.5	Main technical characteristics.....	69
5.1.6	Performance and interference criteria	71
5.1.7	Three-dimensional measurement of atmospheric parameters	71
5.1.7.1	Passive microwave atmospheric vertical sounders	72
5.1.7.2	Mechanism of vertical atmospheric sounding.....	73
5.1.7.3	Utilization of vertical atmospheric sounding	75
5.1.7.4	Characteristics of nadir-looking passive sensors operating in the 60 GHz range	76
5.1.7.5	Passive microwave limb sounders	77
5.1.7.6	Vulnerability to interference of passive microwave sounders	79
5.2	Active sensors	79
5.2.1	Introduction.....	79
5.2.2	Synthetic aperture radars (SARs).....	80
5.2.3	Altimeters.....	82
5.2.4	Scatterometers.....	83
5.2.5	Precipitation radars	85
5.2.6	Cloud profile radars	85
5.2.7	Sensor interference and performance criteria.....	86
5.2.8	Power flux density (PFD) levels	87

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, in the popular press and on the Internet. The public is therefore used to seeing colour-augmented, map-registered images 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.

Many of these have in common the fact that they are generated primarily from data recorded using sensors in the visible and infrared regions of the frequency spectrum that many non-scientists consider “light” and not “radio”. However, many of these products and other products that the public does not regularly see are produced using a variety of microwave frequencies either alone or in conjunction with other measurements.

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

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

There are two classes of spaceborne remote sensing widely employed, **passive** and **active**, that operates under the Earth exploration-satellite service (EESS).

Passive sensing involves the use of pure receivers, with no transmitters involved. The radiation sought by these receivers occurs naturally, usually at very low power levels, which contain essential information on the physical processes under investigation. Of interest are radiation peaks indicating the presence of specific chemicals, or the absence of certain frequencies indicating the absorption of the frequency signals by atmospheric gases. The strength or absence of signals at particular frequencies is used to determine whether specific gases (moisture and pollutants being obvious examples) are present and if so, in what quantity and at what location. A wide variety of environmental information can be sensed through passive sensors, in frequency bands only determined by fixed physical properties (molecular resonance) that cannot hence be changed or ignored, nor are these physical properties able to be duplicated in other bands. Signal strength at a given frequency may depend on several variables, making use of several frequencies necessary to match the multiple unknowns. The use of multiple frequencies is the primary technique used to measure various characteristics of the atmosphere and surface of the Earth.

Active sensing differs from passive sensing in that it involves both transmitters and receivers onboard a satellite. Normally the signal is transmitted and the reflected signal is received by the same satellite. The uses of active sensing vary from measuring the characteristics of the sea surface such as sea wave height and winds 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 implies well-known techniques, typically related to coordination with other users on the basis of power limitations, antenna characteristics, and time and frequency sharing.

A form of vulnerability peculiar to passive remote sensing satellites, and particularly those having a large footprint, derives from the fact that they are subjected to accumulated radiation from a multitude of emitters on the ground, both from in-band emitters and out-of-band emitters. Thus, while a single terrestrial emitter may not radiate enough power to cause harm, a large number of these emitters can still be harmful to the measurements being taken through the aggregation of their signals. This fact is the basis for concerns regarding such things as high density fixed service (HDFS) emissions, ultra wide-band (UWB) applications

and short-range devices (SRD) or industrial, scientific and medical (ISM) devices. It is the spatial density of such emitters rather than their individual characteristics alone which creates a problem. The situation tends to be more and more critical with the increased density of such terrestrial active devices and instances of serious interference have already been reported

Several geophysical parameters contribute, at varying levels, to these natural emissions, which can be observed at a given frequency which presents unique properties. Therefore, measurements at several frequencies in the microwave spectrum must be made simultaneously in order to isolate and to retrieve each individual contribution to the overall natural emissions, and to extract the parameters of interest from the given set of measurements. As a consequence, interference that could impact any of a number of “passive” frequency bands could thus have an impact on the overall measurement of a given atmospheric component.

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

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

There has been considerable interest in recent years in the use of millimetre-wave cloud radars for research applications. The need for improved understanding of the role of clouds in our climate system has a very high priority in climate change research. Together with recent advancements in millimetre-wave radar technology this research need has been the driving force for development of millimetre-wave cloud profiling radars. Operating mainly near 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

Passive microwave radiometry is a tool of fundamental importance for the Earth observation. 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:

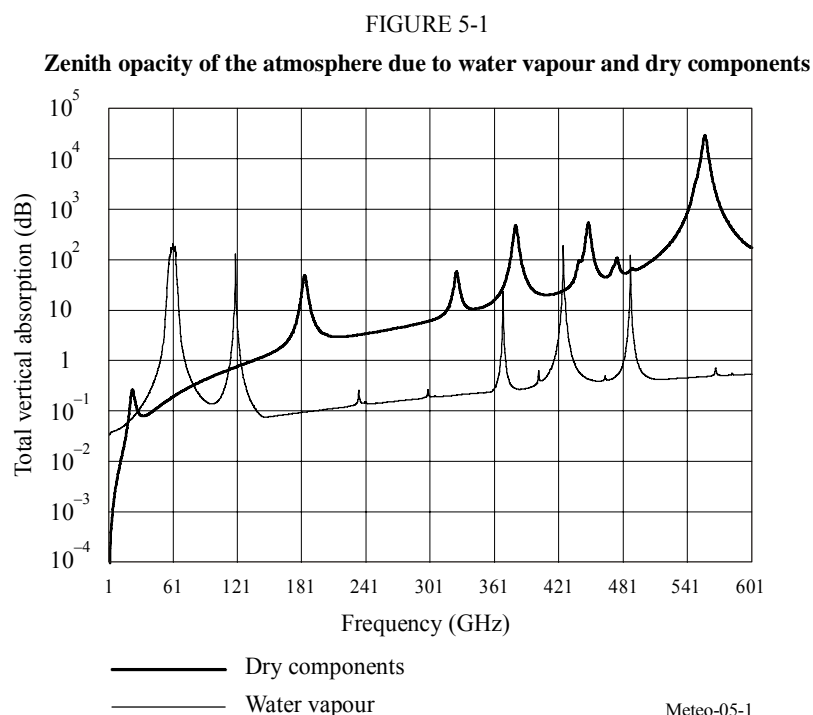
- Earth surface parameters such as soil moisture, sea surface temperature, ocean wind stress, ice extent and age, snow cover, rainfall over land, etc; and
- three-dimensional atmospheric parameters (low, medium, and upper atmosphere) such as temperature profiles, water vapour content and concentration profiles of radiatively and chemically important trace gases (e.g. ozone, nitrous oxide and chlorine).

Microwave techniques enable observation of the Earth’s surface and its atmosphere from Earth orbit even in the presence of clouds, which are largely transparent at frequencies below 100 GHz. This all-weather capability has considerable interest for the Earth observation because more than 60% of the Earth’s surface is usually covered with clouds. In addition to this all-weather capability, passive microwave measurements can

also be taken at any time of day as they are not reliant on daylight. Passive microwave sensing is an important tool widely used for meteorological, climatological, and environmental monitoring and survey (operational and scientific applications), for which reliable repetitive global coverage is essential.

5.1.1 Spectrum requirements

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



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

- frequencies for observation of surface parameters are selected below 100 GHz, where atmospheric absorption is the weakest. One frequency per octave, on average, is necessary; and
- frequencies for observation of atmospheric parameters are very carefully selected mostly above 50 GHz within the absorption peaks of atmospheric gases.

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

TABLE 5-1

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

Frequency band (GHz)	Desired bandwidth (MHz) ⁽³⁾	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 (50)	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 (290)	Water vapour, cloud liquid water
23.6-24	400	Water vapour, cloud liquid water
31.3-31.8	500	Window channel associated with 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 ₂ O
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 No. 5.562F of the RR)
164-167	3 000	Window channel
174.8-191.8	17 000 ⁽¹⁾	H ₂ O (Moisture profiling), cloud, ice, snow, N ₂ O, O ₃
200-209	9 000 ⁽²⁾	H ₂ O, O ₃ , N ₂ O
226-232	6 000 ⁽²⁾ (5 500)	Clouds, CO
235-238	3 000 ⁽²⁾	O ₃
250-252	2 000 ⁽²⁾	N ₂ O
275-277	2 000 ⁽²⁾	N ₂ O
294-306	12 000 ⁽²⁾	N ₂ O, O ₃ , O ₂ , HNO ₃ , HOCl
316-334	10 000 ⁽²⁾	Water vapour profiling, O ₃ , HOCl, H ₂ O, cloud ice
342-349	7 000 ⁽²⁾	CO, HNO ₃ , CH ₃ Cl, O ₃ , O ₂ , HOCl, H ₂ O, window channel, cloud ice and cirrus
363-365	2 000 ⁽²⁾	O ₃
371-389	18 000 ⁽²⁾	Water vapour profiling
416-434	18 000 ⁽²⁾	Temperature profiling
442-444	2 000 ⁽²⁾	Water vapour, cloud ice and cirrus
496-506	9 000 ⁽²⁾	O ₃ , CH ₃ Cl, N ₂ O, BrO, ClO
546-568	22 000 ⁽²⁾	Temperature profiling

TABLE 5-1 (end)

Frequency band (GHz)	Desired bandwidth (MHz)(3)	Main measurements
624-629	5 000 ⁽²⁾	BrO, O ₃ , HCl, SO ₂ , H ₂ O ₂ , HOCl, HNO ₃
634-654	20 000 ⁽²⁾	CH ₃ Cl, HOCl, ClO, H ₂ O, N ₂ O, BrO, O ₃ , HO ₂ , HNO ₃
659-661	2 000 ⁽²⁾	BrO
684-692	8 000 ⁽²⁾	ClO, CO, CH ₃ Cl
730-732	2 000 ⁽²⁾	O ₂ , HNO ₃
851-853	2 000 ⁽²⁾	NO
951-956	5 000 ⁽²⁾	O ₂ , NO, H ₂ O

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

- (1) This bandwidth is occupied by multiple channels.
- (2) This bandwidth is occupied by multiple sensors.
- (3) In some instances, the desired bandwidth exceeds the allocation. In such cases, the current allocated bandwidth is given in brackets.

5.1.2 Observation of Earth's surface features

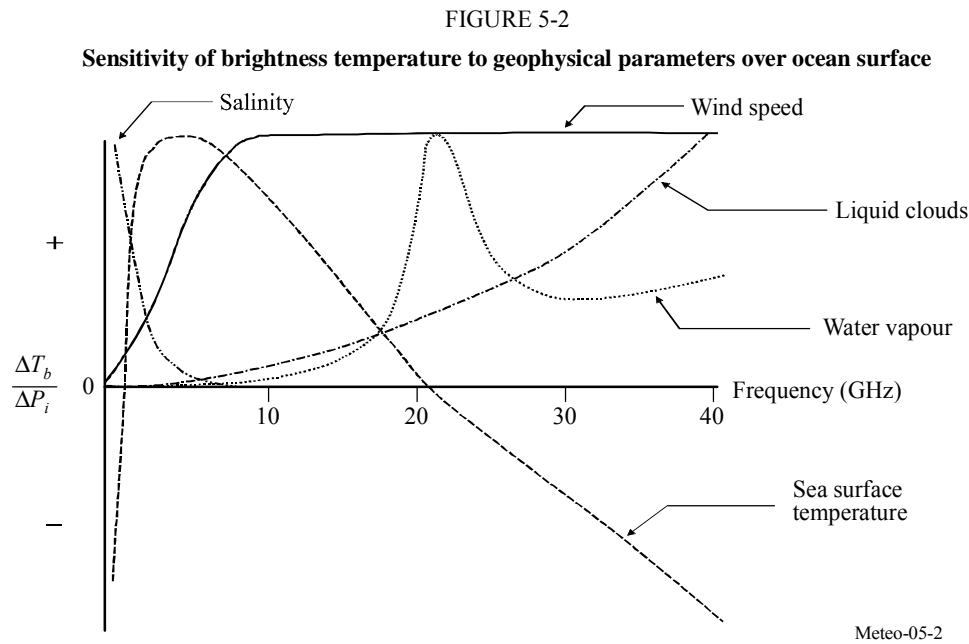
For the measurement of surface parameters (e.g., water vapour, sea surface temperature, wind speed, rain rate, etc.), the so-called radiometric “window” channels must be selected such that a regular sampling over the microwave spectrum from 1 GHz to 90 GHz is achieved (one frequency/octave, on average). 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 and 5-3, which represent the sensitivity of natural microwave emissions to various geophysical parameters depending on frequency. Brightness temperature is a measure of the intensity of radiation thermally emitted by an object, given in units of temperature because there is a correlation between the intensity of the radiation emitted and physical temperature of the radiating body.

5.1.2.1 Observation over ocean surfaces

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

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

- measurements at low frequency, typically around 1.4 GHz, give access to ocean salinity;
- measurements around 6 GHz offer the best sensitivity to sea surface temperature, but contain a small contribution due to salinity and wind speed which can be removed using measurements around 1.4 GHz and around 10 GHz;
- the 17-19 GHz region, where the signature of sea surface temperature and atmospheric water vapour is the smallest, is optimum for ocean surface emissivity, which is directly linked to the wind speed near the surface, or to the presence of sea ice. Ocean surface temperature also has some sensitivity to water vapour total content and to liquid clouds;
- total content of water vapour can be best measured around 24 GHz, while liquid clouds are obtained via measurements around 36 GHz; and
- five frequencies (around 6 GHz, 10 GHz, 18 GHz, 24 GHz and 36 GHz) are necessary for determining the dominant parameters.



5.1.2.2 Observation over land surfaces

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

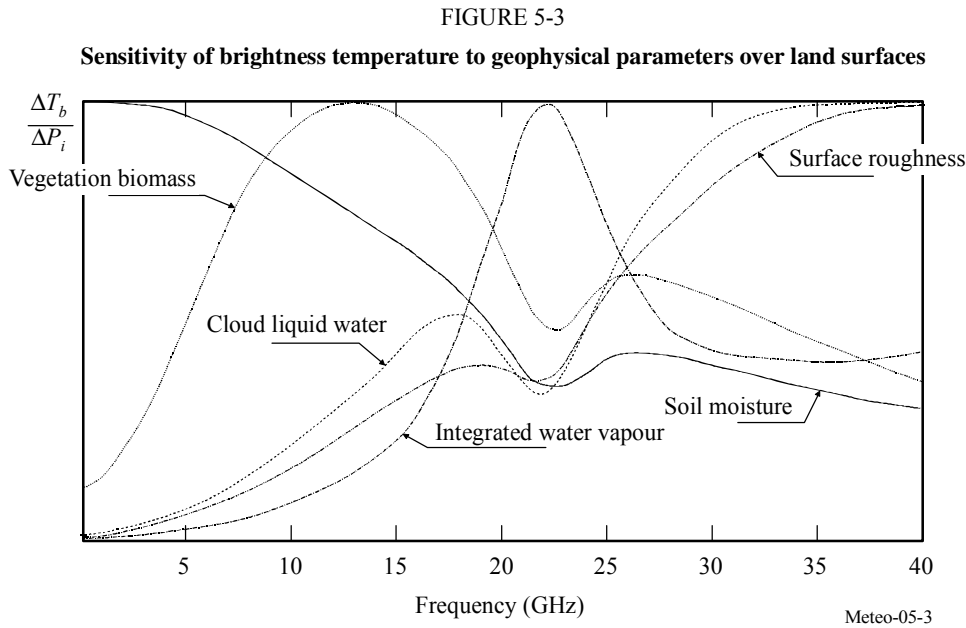
Figure 5-3 shows that over land and for an average temperate area, it is necessary to have access to:

- a low frequency to measure soil moisture (around 1 GHz);
- measurements around 5 GHz to 10 GHz to estimate vegetation biomass once the soil moisture contribution is known;
- two frequencies around the water vapour absorption peak (typically 18-19 GHz and 23-24 GHz) to assess the atmospheric contribution;
- a frequency around 37 GHz to assess cloud liquid water (with use of 18 GHz), and/or vegetation structure (with 10 GHz) surface roughness (with 1 GHz and 5 GHz or 10 GHz).

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

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

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



5.1.2.3 Auxiliary parameters for other remote sensing instruments

Space borne radar altimeters are currently operated on a global basis above ocean and land surfaces, with important applications in oceanography and climatology (see § 5.2.3). In order to remove refraction 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, 24 GHz and 36 GHz.

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

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, ΔT_e that the sensor is able to detect. ΔT_e is given by:

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

where:

B : receiver bandwidth (Hz)

τ : integration time (s)

α : receiver system constant (depends on the configuration)

T_s : receiver system noise temperature (K).

5.1.3.2 Radiometer threshold ΔP

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

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

where:

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

ΔP above is computed using ΔT_e . In the future, T_S will decrease as well as ΔT_e (see equation (5-1)). Therefore ΔP must be computed using a reasonable foreseen ΔT_e rather than the ΔT_e of current technology. In the same manner, the integration time, τ , will likely increase as remote sensing technology develops further (e.g., the so-called “pushbroom” concept). Therefore, the integration time must also be chosen based on reasonable future expectations.

5.1.3.3 Geometric resolution

In the case of two-dimensional measurements of surface parameters, it is generally considered that the -3 dB aperture of the antenna determines the transversal resolution. In the case of three-dimensional measurements of atmospheric parameters, the longitudinal resolution along the antenna axis must also 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

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

5.1.4 Typical operating conditions of passive sensors

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

5.1.4.1 Low Earth-orbiting satellites

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

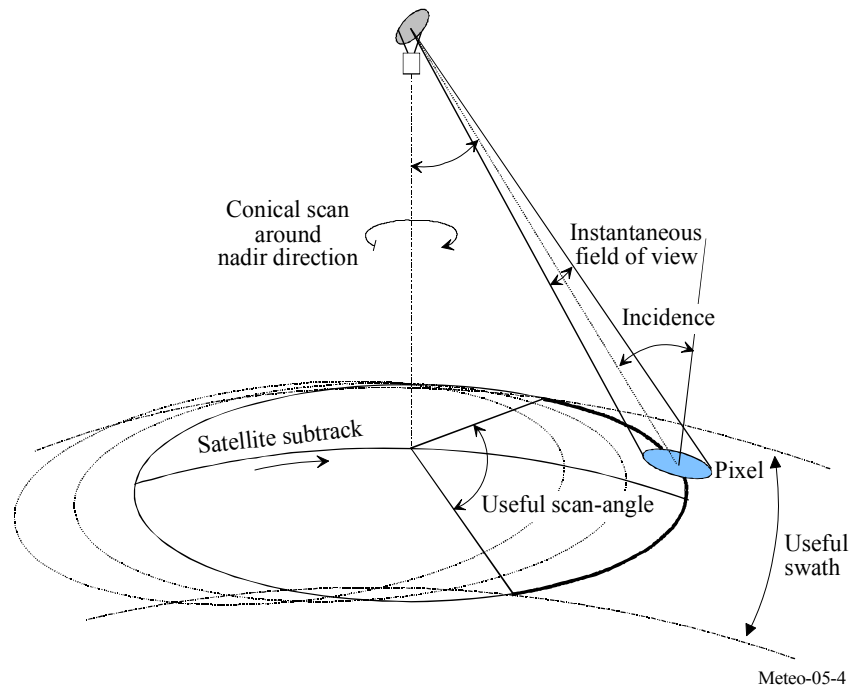
5.1.4.2 Geostationary satellites

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 approximately every 30 min.

5.1.5 Main technical characteristics

Most passive microwave sensors designed for imaging the Earth's surface features use a conical scan configuration (see Fig. 5-4) centred on the nadir (i.e., the point directly below the satellite) direction, because it is important, for the interpretation of surface measurements, to maintain a constant ground incidence angle along the entire scan lines. The geometry of conically scanned instruments is described in Fig. 5-4.

FIGURE 5-4
 Typical geometry of conically scanned passive microwave radiometers



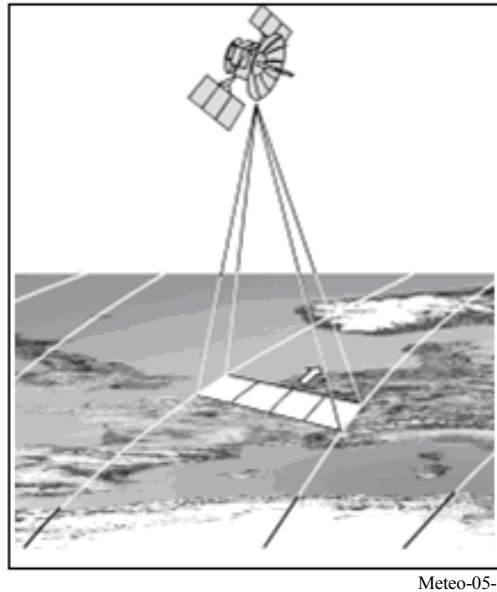
The following are typical geometric characteristics (for 803 km altitude):

- ground incidence angle around 55°
- half-cone angle 46.7° with reference to the nadir direction
- swath width: 1 600 km (limited by the scanning configuration), enabling two complete coverage's to be achieved daily by one instrument, at medium and high latitudes
- pixel size varies with frequency and antenna size, typically from 50 km at 6.9 GHz to 5 km at 89 GHz (based on 2 m effective antenna diameter) and
- scanning period and antenna feed arrangement are chosen in order to ensure full coverage and optimal integration time (and therefore radiometric resolution) at all measured frequencies, at the expense of hardware complexity.

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

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

FIGURE 5-5
Typical geometry of pushbroom passive microwave radiometers



5.1.6 Performance and interference criteria

The performance and interference criteria for spaceborn passive sensors operating in the EESS are contained in Recommendations ITU-R RS.1028 and ITU-R RS.1029 respectively.

5.1.7 Three-dimensional measurement of atmospheric parameters

The electromagnetic spectrum contains many frequency bands where, due to molecular resonances, absorption mechanisms by certain atmospheric gases are taking place (see Fig. 5-1). Frequencies at which such phenomena occur characterize the gas (e.g., O₂, O₃, H₂O, ClO, etc.). The absorption coefficient depends on the nature of the gas, on its concentration, and on its temperature. Combination of passive measurements around these frequencies can be performed from spaceborne platforms to retrieve temperature and/or concentration profiles of absorbing gas. Of particular significance to passive remote sensors operating below 200 GHz are the oxygen resonance frequencies between 50 GHz and 70 GHz, at 118.75 GHz, and the water vapour resonance frequency at 183.31 GHz.

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

$$I = \alpha \cdot L \quad (5-3)$$

where:

I : 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/(m² · sr · Hz))

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

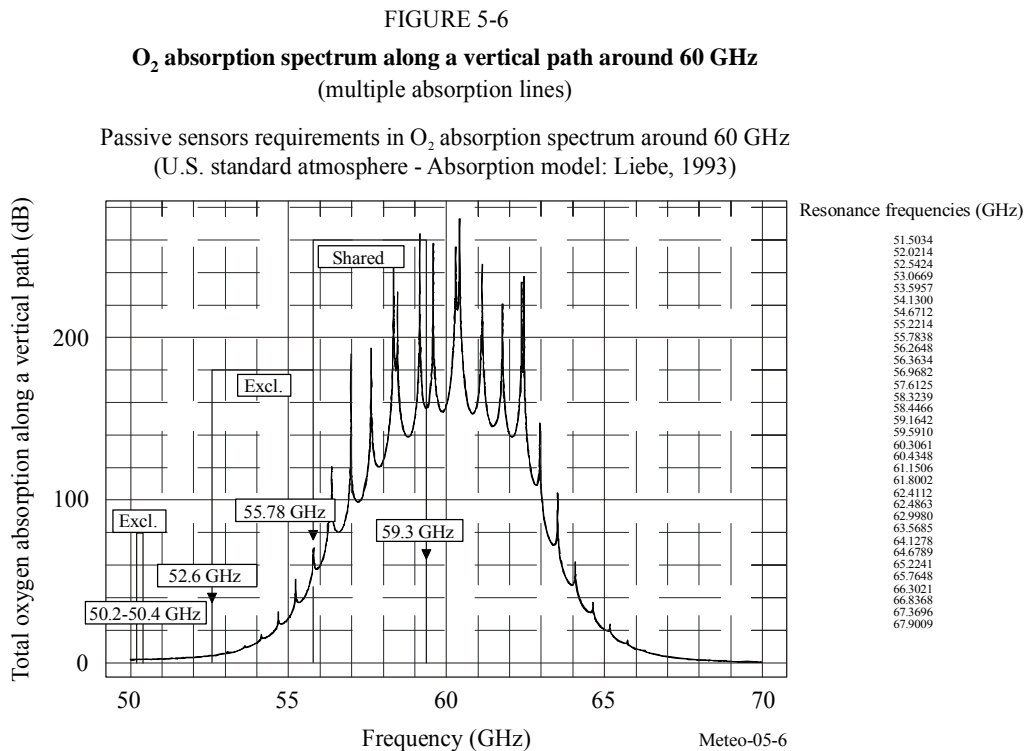
α : characterizes the gas (O₂, CO₂, H₂O, O₃, etc.).

Two atmospheric gases, CO₂ and O₂, play a predominant role in passive sensing for meteorology because their concentration and pressure in the atmosphere (two parameters which determine the absorption ratio α) are almost constant and known all around the globe. It is therefore possible to retrieve atmospheric temperature profiles from radiometric measurements at various frequencies in the appropriate absorption bands (typically in the infrared region around 15 μ m for CO₂, and in the microwave region around 60 GHz and 118.75 GHz for O₂).

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 this case, the knowledge of atmospheric temperature profiles is mandatory in order to retrieve the unknown vertical concentration profiles of these gases.

5.1.7.1 Passive microwave atmospheric vertical sounders

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



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

FIGURE 5-7
O₂ absorption spectrum along a vertical path around 118.75 GHz
 (one unique absorption line)

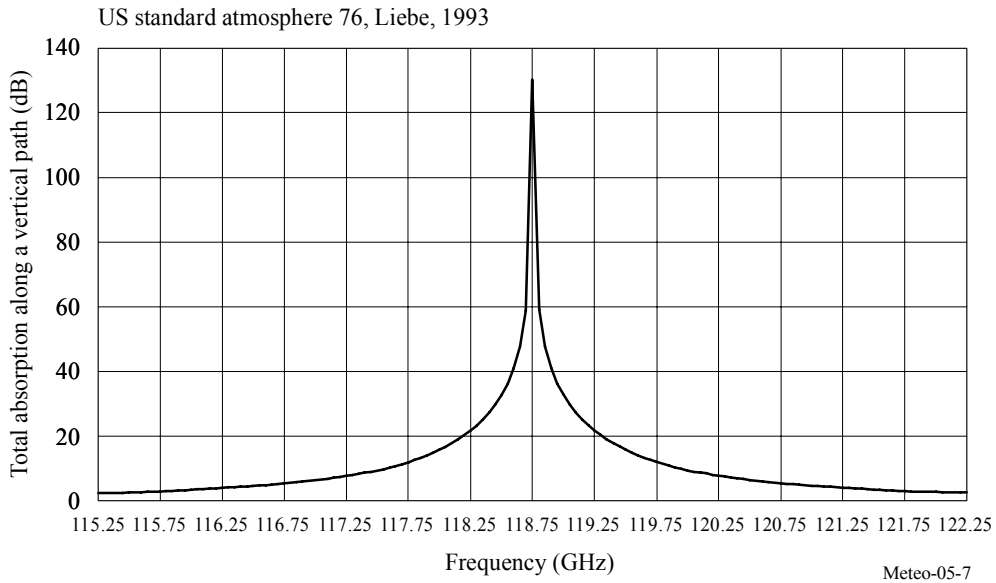
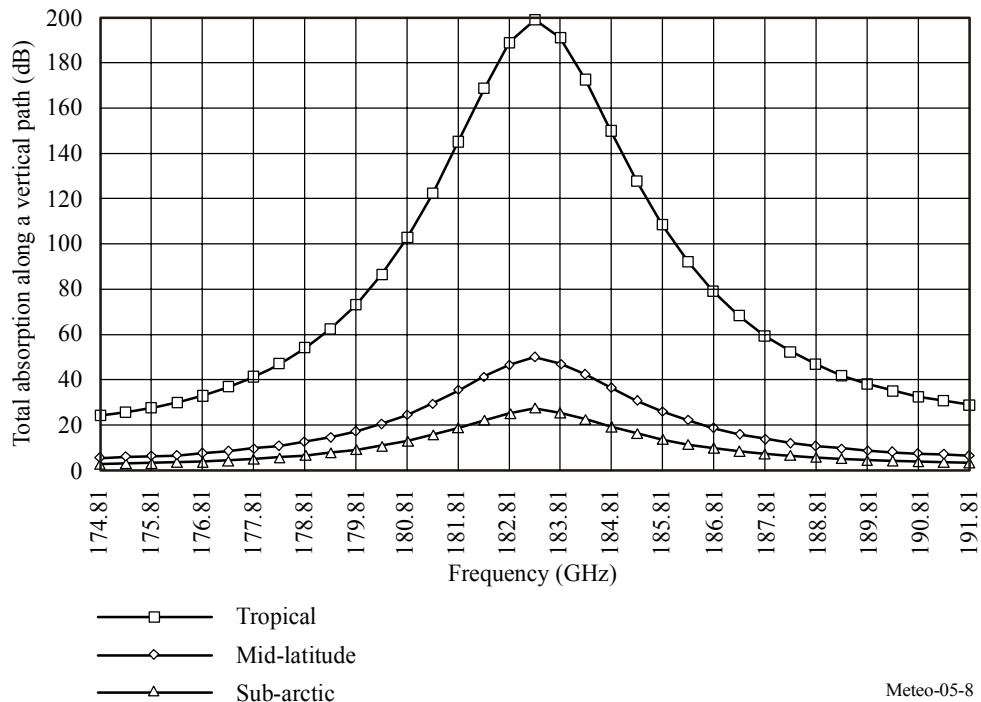


FIGURE 5-8
Water vapour absorption spectrum along a vertical path around 183.31 GHz



5.1.7.2 Mechanism of vertical atmospheric sounding

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

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

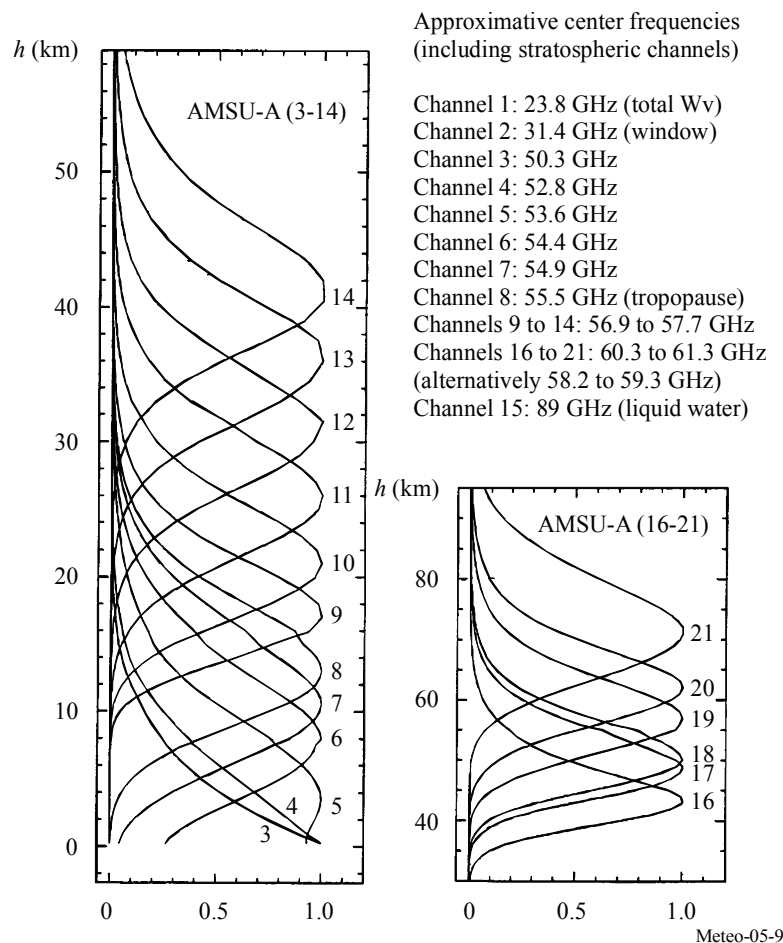
Integration of the radiative transfer equation along the path from Earth's surface to the satellite reflects this mechanism, and results in a weighting function which describes the relative contribution of each atmospheric layer, depending on its altitude, and which represents also the longitudinal (vertical)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

The peak of the weighting function 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 (see Fig. 5-9 for example). They are extremely carefully selected within the absorption band, covering a wide range of absorption levels in order to obtain the best atmospheric samples from the surface up to stratospheric altitudes.

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

FIGURE 5-9

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



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 O₂ absorption spectrum. As such, they must have similar geometric and radiometric performances and must receive similar protection against interference. In Fig. 5-9, it can be seen that:

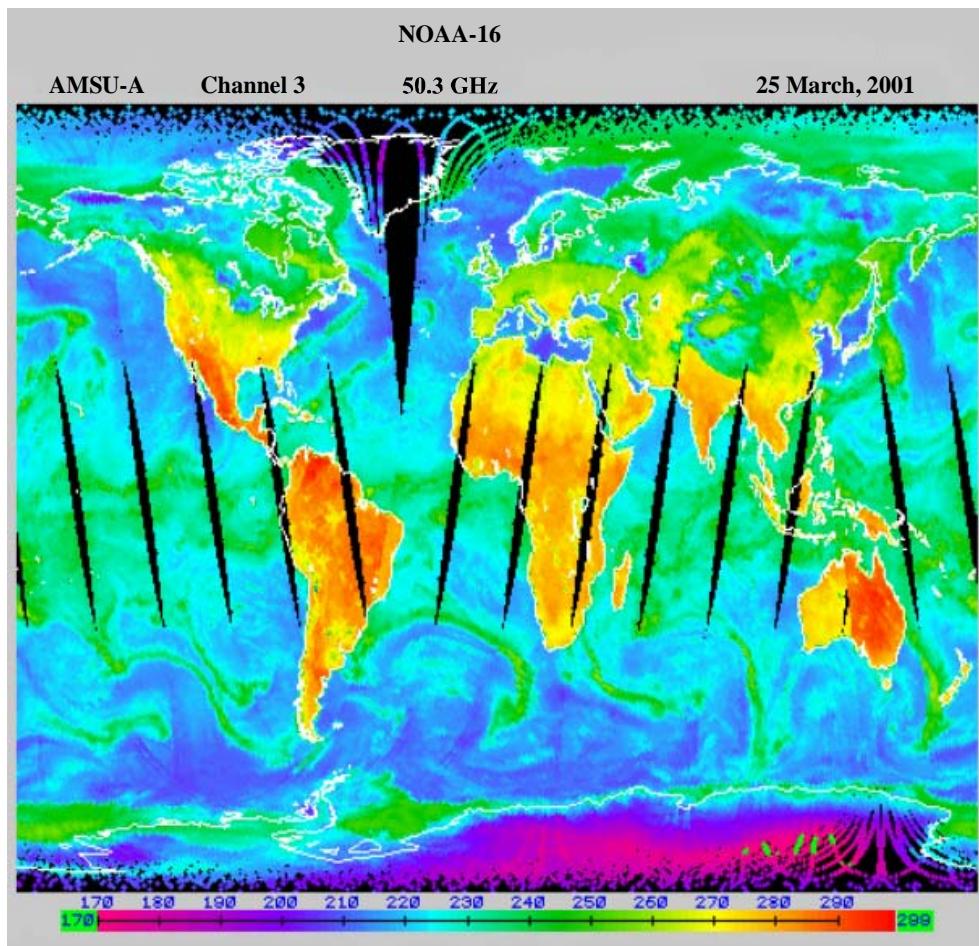
- Channel 1 is close to a H₂O absorption peak. It is used to retrieve the total water vapour content along the line of sight, and to determine the corrections, which are necessary in the other channels.
- Channel 2 has the lowest cumulated effects due to oxygen and water vapour. It is the optimum window channel to see the Earth's surface, and is the reference for the other channels.

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

5.1.7.3 Utilization of vertical atmospheric sounding

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

FIGURE 5-10
Global composite of temperature (K) measurements from AMSU-A



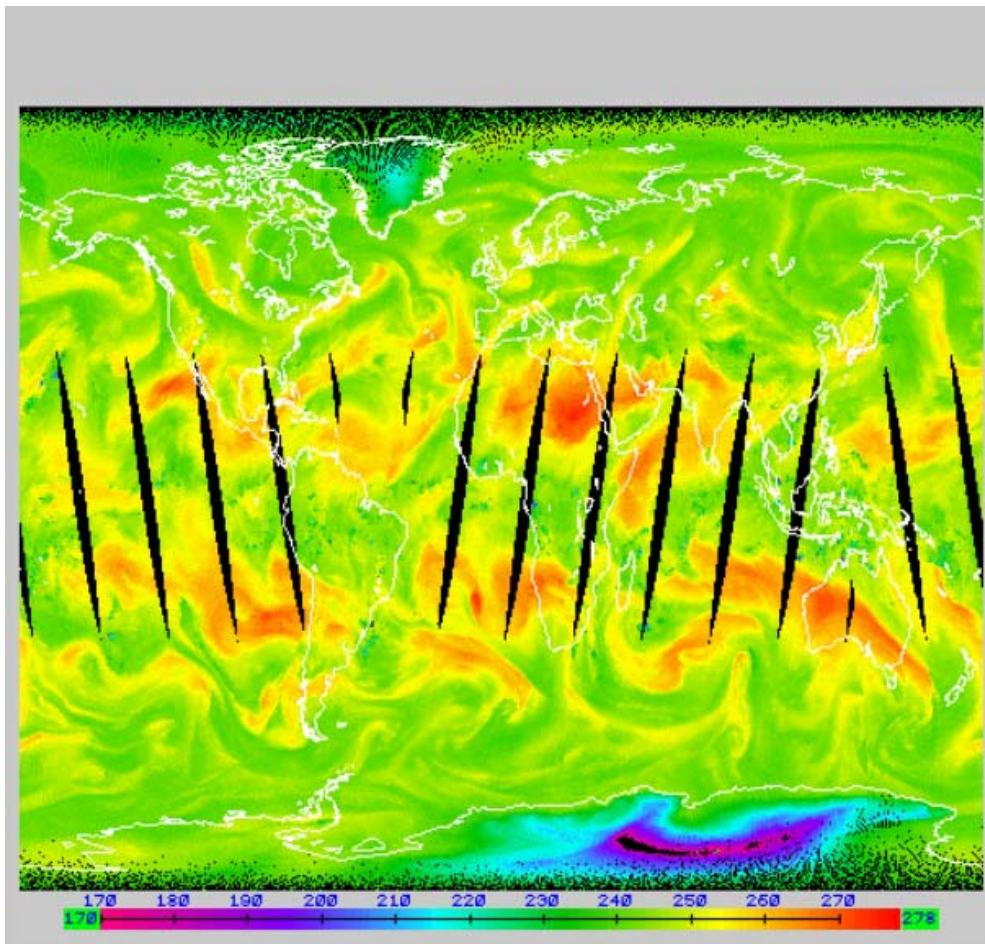
Meteo-05-10

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

The NWP models use partial differential Navier-Stokes equations. Because they simulate highly unstable atmospheric mechanisms, they are extremely sensitive to the quality of the initial three dimensional profiling. This problem has been described by Lorentz and is now clearly explained by the “chaos theory”. To run NWP models, the most powerful super computers are needed.

FIGURE 5-11

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



In order to increase effectiveness of NWP models, it will be necessary to improve and increase the initialization of the models at least every 6 h on a worldwide basis and at a resolution of 50 km for global NWP and 10 km for regional/local NWP. In the future, it will be necessary to get information approximately every 3 h.

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

Most passive microwave sensors designed for measuring tropospheric/stratospheric parameters, are nadir-looking instruments. They use a cross-track mechanical (current) or push-broom (future) scanning configuration in a plane normal to the satellite velocity containing the nadir direction. This configuration provides optimum field-of-view (FOV) and optimum average quality of data. Typical characteristics of temperature sounders working around 60 GHz and operated on board low Earth orbiting satellites are given in Table 5-3.

TABLE 5-3

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

5.1.7.5 Passive microwave limb sounders

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

- the longest path is used, which maximizes signals from low-concentration atmospheric minor constituents, and renders possible soundings at high altitudes;
- the vertical resolution is determined by the radiative transfer through the atmosphere and by the vertical field of view of the antenna. A typical example is shown in Fig. 5-12;
- the horizontal resolution normal to the line of sight is determined principally by the horizontal field of view of the antenna and the smearing due to the satellite motion;
- the horizontal resolution along the line of sight is principally determined by the radiative transfer through the atmosphere;
- the space background is optimum for emission measurements; and
- limb measurements are extremely vulnerable to interference caused by inter-satellite links.

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

- scan the atmosphere vertically in the 15-120 km altitude range, in two side-looking orthogonal directions;
- typical vertical resolution for profile measurements (weighting functions width at half value) is about 3 to 6 km, as shown on Fig. 5-12;
- typical horizontal resolution is 30 km across and 300 km along the direction of observation;
- complete profiles are obtained in less than 50 s; and
- observes thermal limb emission in five microwave spectral regions (see Table 5-4).

FIGURE 5-12

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

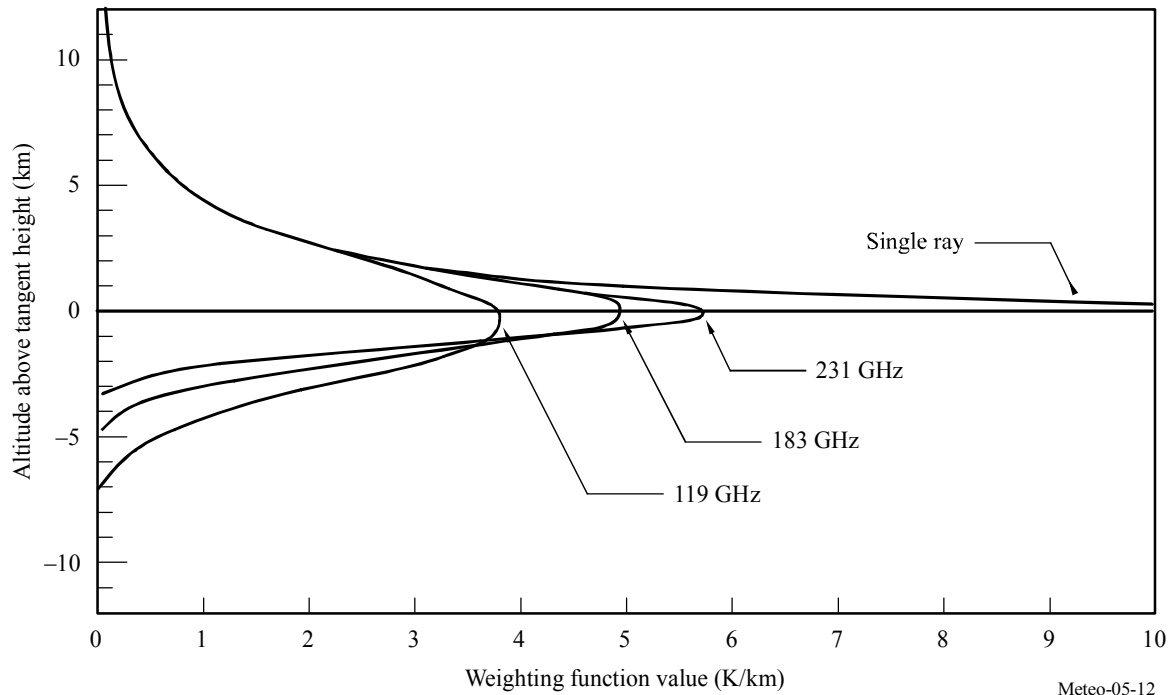


TABLE 5-4

Example measurement objectives of typical microwave limb sounders and spectral regions

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

The new generation of microwave limb sounders measure lower stratospheric temperature and concentrations of H₂O, O₃, ClO, BrO, HCl, OH, HO₂, HNO₃, HCN, and N₂O, for their effects on, and diagnoses of, ozone depletion, transformations of greenhouse gases, and radiative forcing of climate change. MLS also measures upper tropospheric H₂O, O₃, CO, and HCN for their effects on radiative forcing of climate change and for diagnoses of exchange between the troposphere and stratosphere.

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

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

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

5.1.7.6 Vulnerability to interference of passive microwave sounders

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

The passive sensors are therefore extremely vulnerable to interference, even at very low power levels, 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 (should it be detectable) may render impossible the recognition of new developing weather systems, and vital indications of rapidly developing potentially dangerous storms may be missed.
- If not detected, which is more than likely, corrupted data will be mistaken for valid data and the conclusions derived from the analysis of these corrupted data will be seriously flawed.
- For climatological studies and particularly for “global change” monitoring, interference may lead to misinterpretation of climate signals.

Recommendations ITU-R RS.1028 and ITU-R RS.1029 provide the required radiometric performances and the permissible interference levels respectively.

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 5-5.

TABLE 5-5

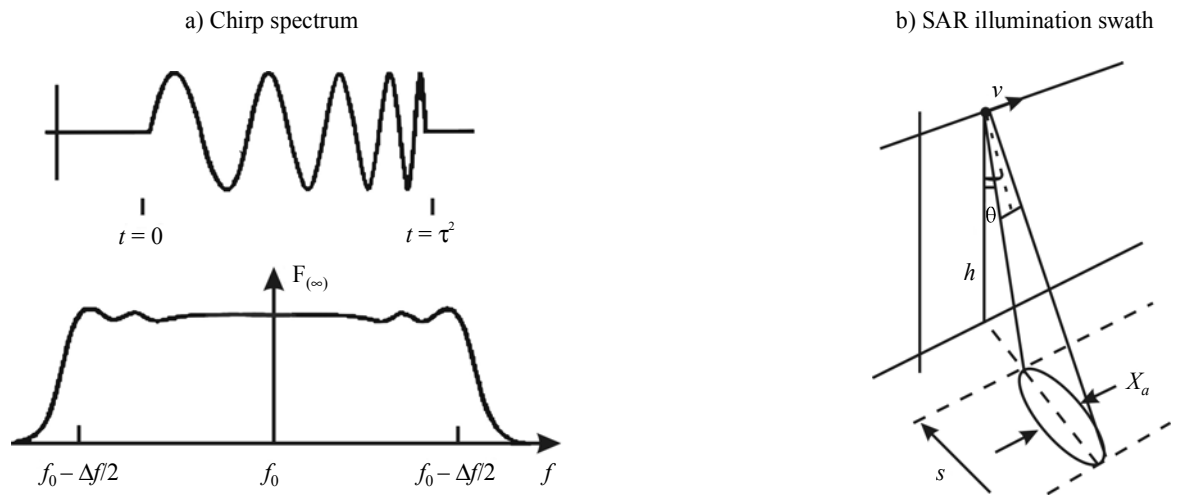
Active spaceborne sensor characteristics

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 – Two conically scanning beams	Nadir-looking	Nadir-looking
Footprint/-dynamics	– Fixed to one side – ScanSAR	Fixed at nadir	– Fixed in azimuth – Scanning	Scanning across nadir track	Fixed at nadir
Antenna beam	Fan beam	Pencil beam	– Fan beams – Pencil beams	Pencil beam	Pencil beam
Radiated peak power (W)	1 500-8 000	20	100-5 000	600	1 000-1 500
Waveform	Linear FM pulses	Linear FM pulses	Interrupted CW or short pulses	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)

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

FIGURE 5-13
Chirp spectrum and SAR illumination swath



Meteo-05-13

FIGURE 5-14
SAR image of the Dead Sea along the West Bank between Israel and Jordan



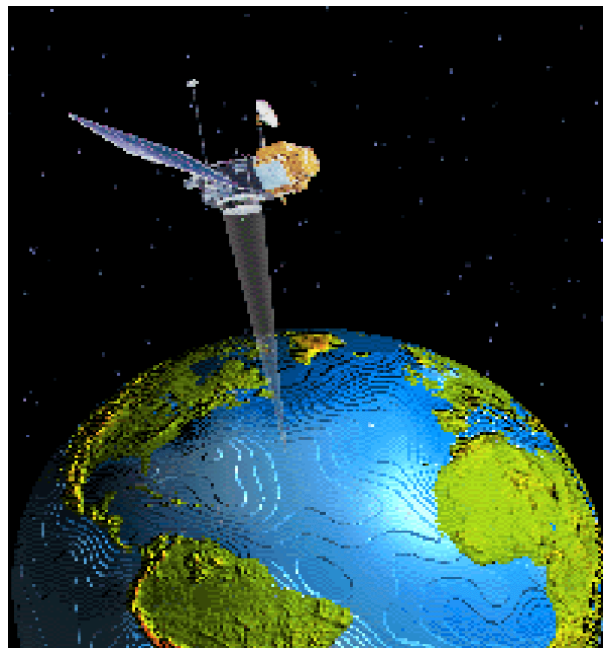
Meteo-05-14

5.2.3 Altimeters

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

FIGURE 5-15

Microwave satellite altimeter



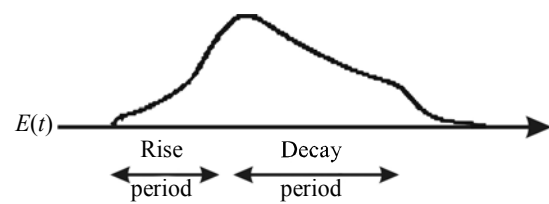
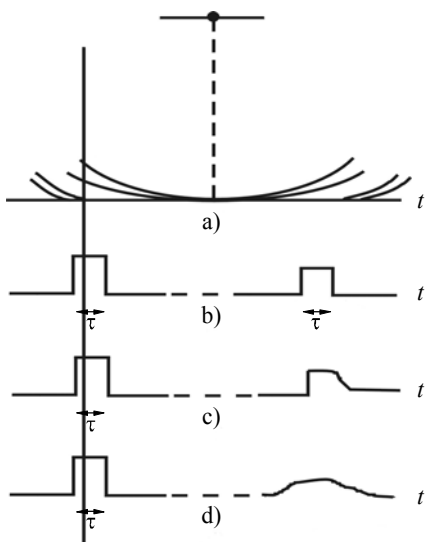
Meteo-05-15

FIGURE 5-16

Illustration of altimeter return and spreading of return pulse

a) Illustration of altimeter return

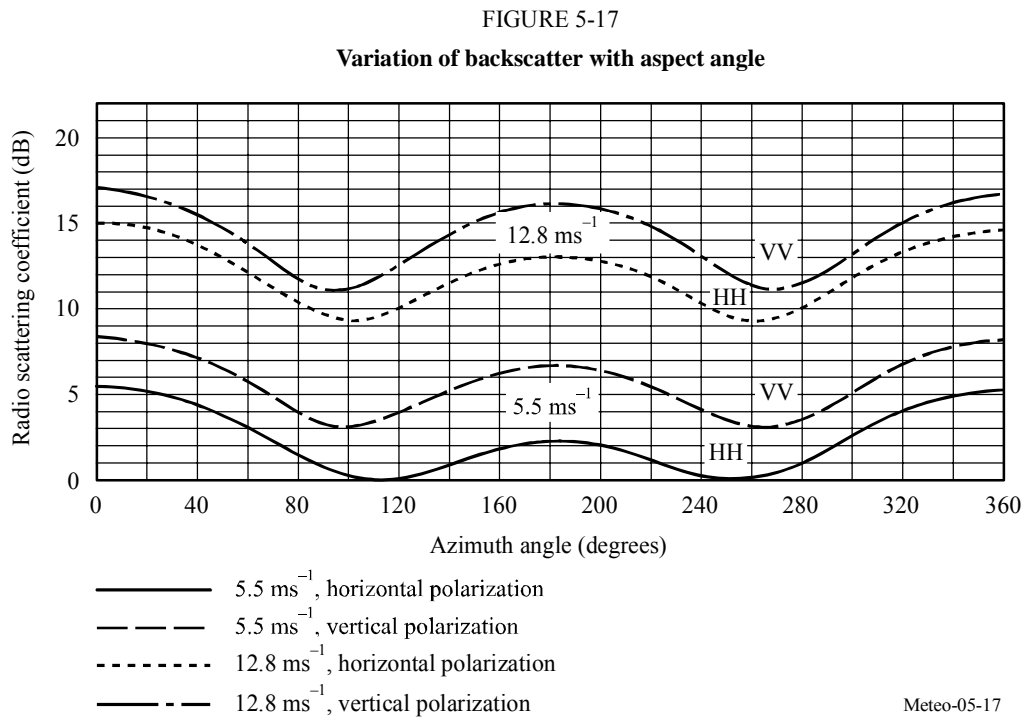
b) Spreading of return pulse



Meteo-05-16

5.2.4 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 5-17 shows the variation of backscatter level with aspect angle relative to the wind velocity vector direction.



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

FIGURE 5-18
Scatterometer fixed footprint

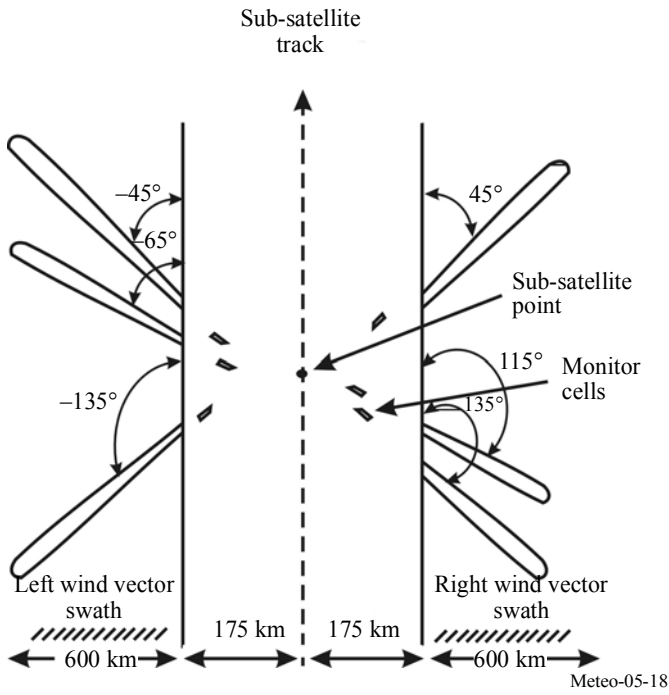


FIGURE 5-19
Scatterometer pencil beam scan

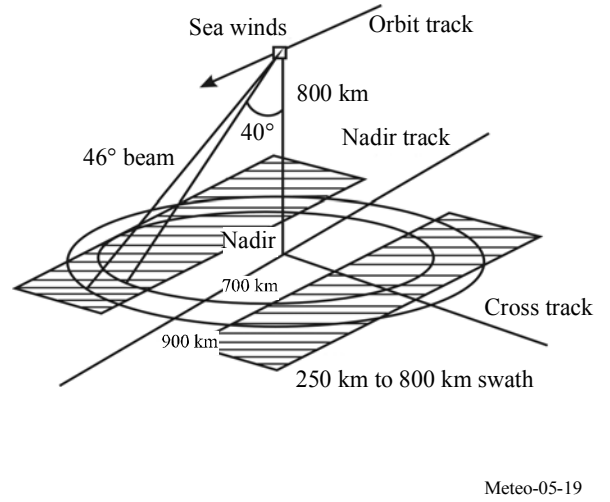
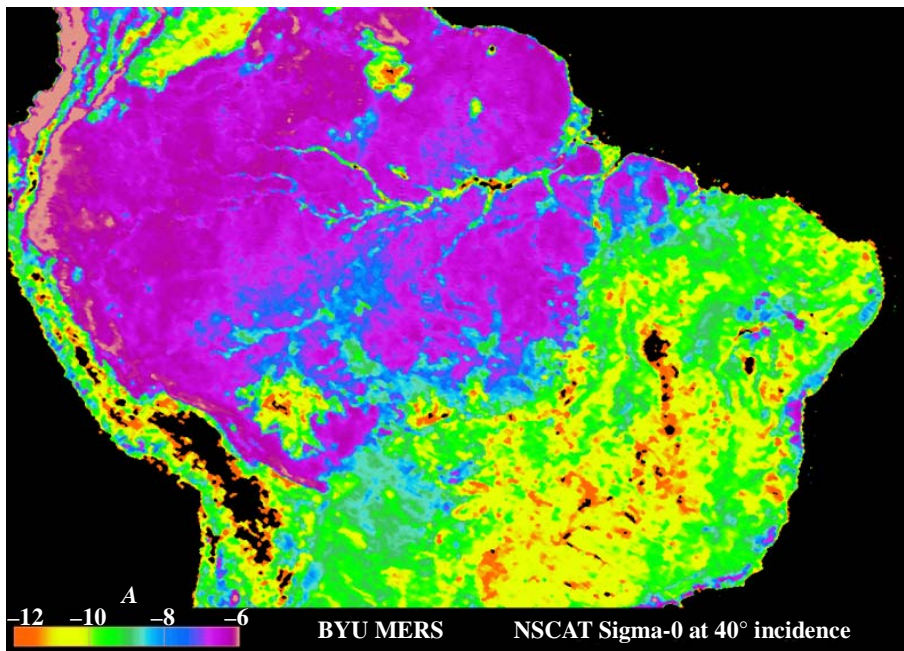


Figure 5-20 shows an example radar image taken from the NSCAT scatterometer of the Amazon rainforest in South America.

FIGURE 5-20
NSCAT scatterometer 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.

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

$$\sigma_b = \pi^5 |K_W|^2 D^6 / \lambda^4 = \pi^5 |K_W|^2 Z / \lambda^4 \quad (5-4)$$

where:

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

D : diameter of the drop (m)

λ : wavelength of the radar (m)

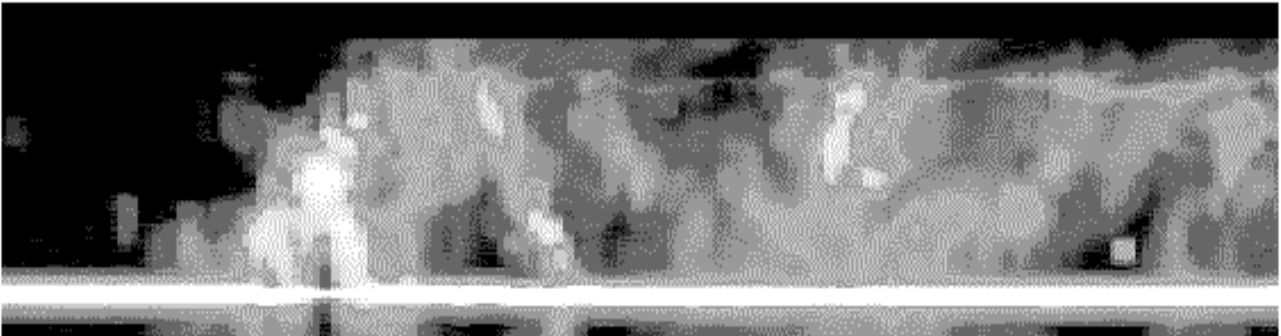
Z : radar reflectivity factor.

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

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

FIGURE 5-21

Synthesized reflectivity from precipitation reflectivity measurements



Meteo-05-21

5.2.6 Cloud profile radars

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

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

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

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

where:

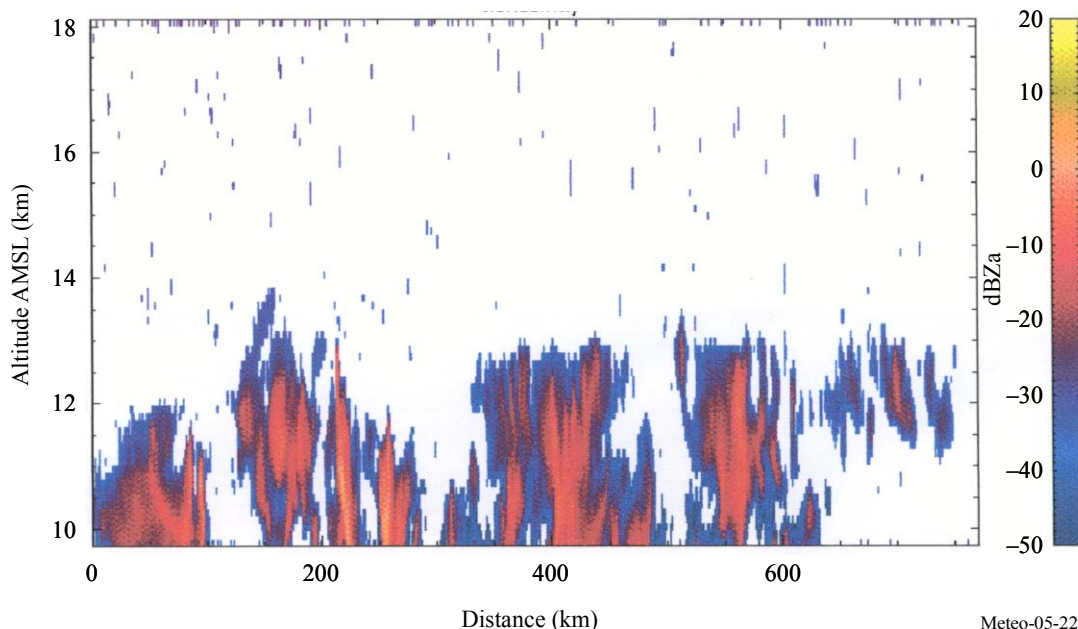
- \tilde{P} : return power level of the clouds (mW)
- P_T : radar transmit power (W)
- G : antenna gain (numeric)
- t : pulse width (μ s)
- θ_r : 3 dB antenna beamwidth (degrees)
- K_W : dielectric factor of the cloud water content
- Z_r : cloud reflectivity factor (mm^6/m^3)
- r_0 : range distance (km)
- λ : radar wavelength (cm)
- l : signal loss due to atmospheric absorption
- l_r : radar system loss.

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

FIGURE 5-22

Example of cirrus cloud reflectivity

Tropical cirrus observed during transit from Hawaii to New Zealand



Meteo-05-22

5.2.7 Sensor interference and performance criteria

The criteria for performance and interference are provided in Recommendation ITU-R RS.1166 for the various types of active spaceborne sensors.

5.2.8 Power flux density (PFD) levels

The characteristics of the various types of active spaceborne sensors as shown in Table 5-5 indicate that the transmitted peak power and therefore the power levels received at the Earth's surface will vary significantly in level. Table 5-6 shows the active sensor power flux density levels at the Earth's surface for some typical sensor configurations.

TABLE 5-12
Typical power flux density levels at Earth's surface

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

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ITU-R texts

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

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

Recommendation ITU-R RS.1028 – Performance criteria for satellite passive remote sensing

Recommendation ITU-R RS.1029 – Interference criteria for satellite passive remote sensing

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

CHAPTER 6**OTHER RADIOCOMMUNICATION SYSTEMS
FOR METEOROLOGICAL ACTIVITIES**

	<i>Page</i>
6 Introduction.....	90
6.1 Dissemination systems.....	90
6.2 Hydrological systems.....	90
6.3 Radiocommunications for remote meteorological and environmental systems.....	91
6.4 Meteorological uses of Global Navigation Satellite Systems (GNSSs).....	91
6.5 Lightning detection systems.....	92
6.6 Ground-based remote sensing.....	94
6.7 Unmanned Aircraft Systems (UAS)	95

6 Introduction

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

6.1 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 (terrestrial and satellite) and on MetSat downlinks.

Over the years, high frequency radio has been used by many administrations to provide weather and warning information to ships at sea and to 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.

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

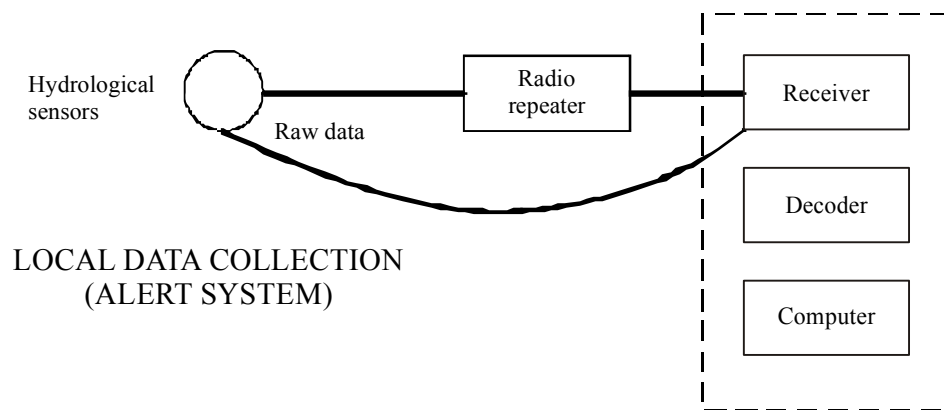
6.2 Hydrological systems

Floods are a natural and inevitable part of life in much of the world, and systems that can aid in predicting their occurrence, location and magnitude have saved many lives and a significant amount of property. Advance knowledge permits the evacuation of vulnerable populations, the construction of levees and dams, and the relocation of such valuable and vulnerable property as can be removed. Hydrological systems typically are used to measure such things as precipitation, stream height and the depth of snow pack, all of which are required in the prediction and early warning of flooding. They are also useful in estimating the availability of water resources.

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

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

FIGURE 6-1
Schematic of a hydrologic system



Sensor data processed locally at computer site.
No dedicated communications between other computer processing sites.
Coverage area limited to radio range of sensors and repeaters.

Meteo-6-1

6.3 Radiocommunications for remote meteorological and environment systems

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

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

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

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

6.4 Meteorological uses of Global Navigation Satellite Systems (GNSSs)

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

- *Location of mobile meteorological observing platforms:* for example radiosondes carried by weather balloons, dropsondes falling on parachutes, unmanned aircraft carrying meteorological sensors (see Chapter 3), or marine meteorological systems such as ocean buoys.
- *Very accurate synchronization of time:* between remote observing sites, as required for instance by lightning detection systems (see § 6.5).

- *Measurement of total water vapour in the atmosphere:* derived from the phase delay in the GPS signals received by ground based receivers. Computation of total water vapour requires extremely accurate computations of the position of the various GPS satellites and the timing of the satellite clocks. The position of the ground receiver must also be known very accurately. The GPS receivers are usually installed on a fixed mount suitable for accurate tracking of position on the Earth's surface as well as providing meteorological information. Thus, the measurements may be produced as a byproduct of geodetic/ seismological observations or from sensors deployed specifically by meteorologists. Phase delays introduced in signal transmission through the ionosphere are identified from the differences in the phase delays between the two GPS frequencies, L1 and L2. If the surface pressure and temperature are known, the dry hydrostatic phase delay introduced by the atmosphere can be estimated, and the remaining phase delay is then proportional to the total water vapour along the path to the satellite. The GPS sensor at the surface receives GPS signals from many directions in a short period of time. Thus, it is possible to estimate the total water vapour in the vertical, as well as gradients in total water vapour in the horizontal direction around the sensor. This technique has relevance for atmospheric propagation studies, since it allows a direct measurement of water vapour content along a slant path from the ground receiver to a satellite. See also [Coster *et al.*, 1997].
- *Measurement of temperature and relative humidity as a function of height derived from space-based occultation measurements of the GPS signals:* in this application, a receiver on an independent satellite receives signals from the GPS constellation passing through the atmosphere at grazing incidence to the Earth's surface. The refraction of the GPS signals is measured at a range of heights above the Earth's surface. This allows the refractive index of the air to be derived as a function of height. At upper levels in the neutral atmosphere, relative humidity is very low and the refractive index of air can be assumed to be directly dependent on temperature. At levels closer to the surface below the tropopause, both temperature and partial pressure of water vapour influence the refractive index. The partial pressure of water vapour can be estimated if the temperature is already known from another source. The measurement of meteorological variables derived from this technique will have a better vertical resolution than the output from nadir viewing passive sensing radiometers, see Chapter 5, but will be averaged over relatively long distances in the horizontal. As with the total water vapour measurement, this technique requires very precise timing and knowledge of the position of both satellites. GNSS receivers are planned for the next generation of polar orbiting meteorological satellites.

6.5 Lightning detection 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 is either determined by measuring the direction of arrival of the associated spheric (atmospheric wave), or by measuring the time of arrival of the spheric, or a combination of both.

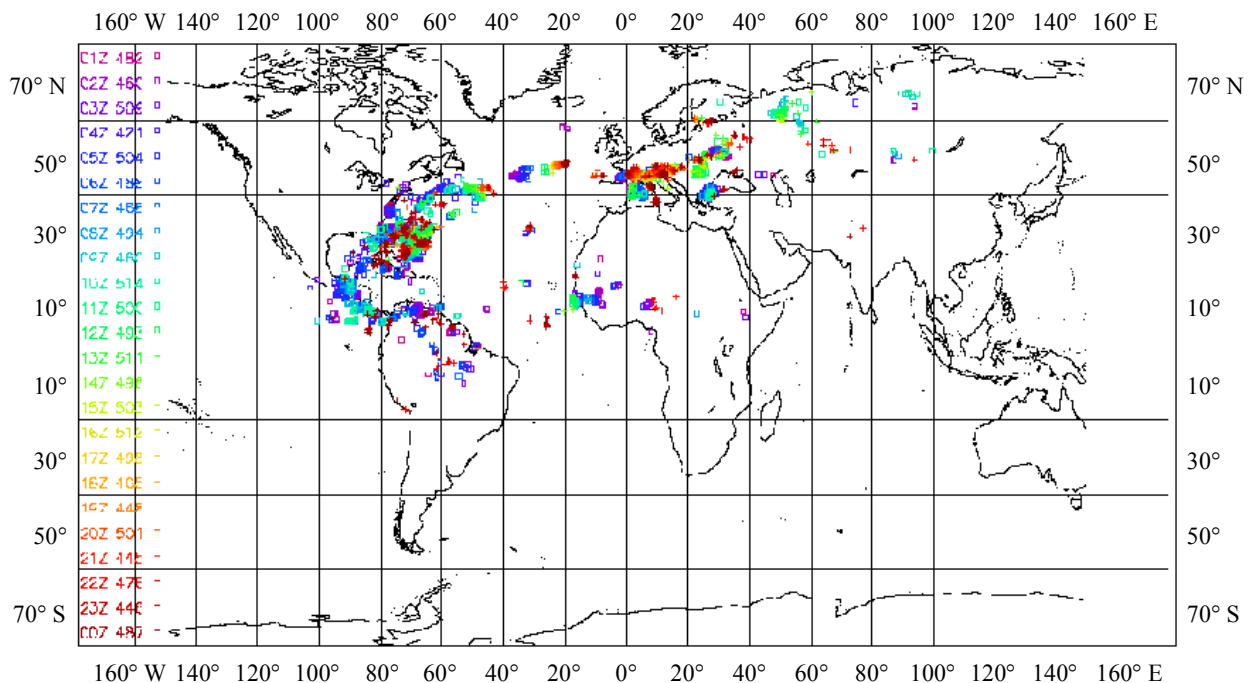
Measurements are required at more than three widely spaced sensing sites. The number of sites used in practice is usually larger than the minimum in order to improve the reliability of the reported locations. Time of arrival systems usually provide more accurate locations than direction finding systems when observing at ranges over several hundred kilometres. This is due to the direction of reception of skywaves sensed at the site, which usually differs slightly from the actual direction of the discharge, and will vary according to the

state of the surface layers near the sensing site. Time of arrival systems usually rely heavily on GPS radionavigation signals to achieve the necessary time synchronization at the various sensing sites. All systems rely on cost effective, reliable communications from the remote sites to the central processor. The radio frequency used to locate lightning activity varies according to the area of monitoring required and the specific purpose of the system.

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

FIGURE 6-2

Map of lightning data for one day for long range system



11 581 thunderstorm records in this 24 h period

Meteo-6-2

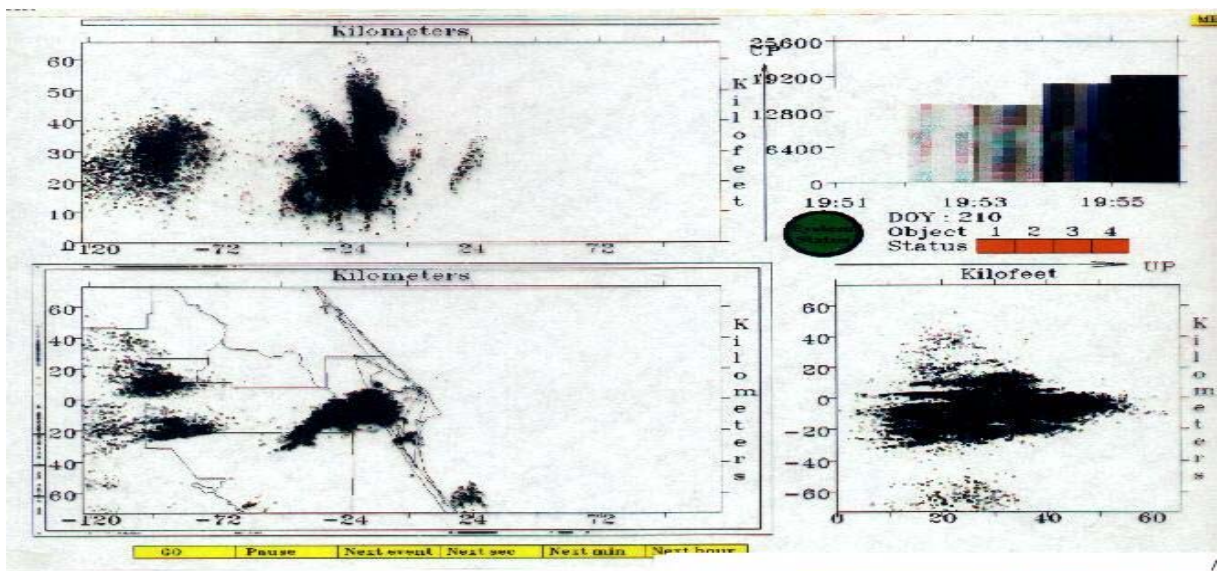
The most widely used operational systems cover a more limited area in detail. In this case, the spherics are observed at higher frequencies centred around 200 kHz (the wideband receivers used are most sensitive in the middle of their range of 1 kHz to 350 kHz), and the sensing sites are usually spaced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

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

while the SAFIR (Surveillance et Alerte Foudre par Interférométrie Radioélectrique) system uses 110 to 118 MHz). Figure 6-3 shows the real-time LDAR display. The storms must remain within line-of-sight if all the activity is to be observed. This requires that the ground sensors be located in a short baseline configuration – the sensors need to be 30 km apart, and about 50 m from the ground to fulfill 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. 6-3 shows LDAR data on a map of the East coast of Florida (partially shown). The data are then projected on an East-West vs. altitude panel (upper left) and a North-South vs. altitude panel (lower right, note that this panel is turned 90° on its side). A histogram (upper right) displays the data in five one-minute increments.

FIGURE 6-3
Real-time LDAR display



Meteo-6-3

6.6 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 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 (in particular at 142 GHz) also benefits from a significant number of ground-based radiometry sites.

6.7 Unmanned Aircraft Systems (UAS)

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

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

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ANNEX 1

ACRONYMS AND ABBREVIATIONS COMMONLY USED
IN METEOROLOGY

A		A (cont.)	
A/D	Analog-to-digital	ATOVS	Advanced TIROS Operational Vertical Sounder
AAAS	American Association for the Advancement of Science	ATSR	Along-Track Scanning Radiometer
AARS	Automated Aircraft Reporting System	AVCS	Advanced Video Camera System
ABSN	Antarctic Basic Synoptic Network	AVHRR	Advanced Very High Resolution Radiometer
ACARS	Aircraft Communications Addressing and Reporting System	AWIPS	Advanced Weather Information Processing System
ACCAD	Advisory Committee on Climate Applications and Data	B	
ACMAD	African Centre of Meteorological Applications for Development	BCD	Binary Coded Decimal
ADAS	Airborne Data Acquisition System	BER	Bit Error Rate
ADC	Analog-to-Digital Converter	BPS	bits per second
ADEOS	Advanced Earth Observation Satellite (Japan)	BPSK	Binary Phase Shift Keying
ADP	Automatic Data Processing	BR	ITU Radiocommunication Bureau
ADPE	Automatic Data Processing Equipment	BW	Bandwidth
AFC	Automatic Frequency Control	C	
AFOS	Automatic Forecasting and Observing System	C/N_0	Carrier-to-noise density ratio
AGC	Automatic Gain Control	C&DH	Command and Data Handling
AGRHYMET	Regional Training Centre for Agrometeorology and Operational Hydrology and its Applications	Caem	Commission for Aeronautical Meteorology
AIRS	Advanced Infrared Sounder (NASA instrument)	CAgM	Commission for Agricultural Meteorology
ALC	Automatic Level Control	CAS	Commission for Atmospheric Sciences
AM	Amplitude Modulation	CBS	Commission for Basic Systems
AMDAR	Aircraft Meteorological Data Relay	CCD	Charge Coupled Device
AMI	American Meteorological Society	CCIR	International Radio Consultative Committee (see ITU-R)
AMSR	Advanced Meteorological Temperature Sounder	CCI	Commission for Climatology
ANSI	American National Standards Institute	CCRS	Canada Centre for Remote Sensing
AOPC	Atmospheric Observation Panel for Climate	CCSDS	Consultative Committee for Space Data Systems
AOS	Acquisition of Signal	CDA	Command and Data Acquisition
APT	Automatic Picture Transmission	CDAS	Command and Data Acquisition Station
ARGOS	Data collection and location system on NOAA series satellites	CEOS	Commission on Earth Observation Satellites
ASCII	American Standard Code for Information Interchange	CERES	Cloud and Earth's Radiative Energy System
ASIC	Application Specific Integrated Circuit	CGMS	Co-ordination Group for Meteorological Satellites
ATMS	Advanced Technology Microwave Sounder (NPOESS/NASA)	CHy	Commission for Hydrology (WMO)
		CIESIN	Consortium for International Earth Science Information Networks
		CIMO	Commission for Instruments and Methods of Observation

C (cont.)

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

D (cont.)

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 für Luft- 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

E (cont.)

EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
ENSO	<i>El Niño</i> /Southern Oscillation
ENVISAT	Environmental Satellite
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	Engineering Test Model
ETM	Enhanced Thematic Mapper
ETS	Engineering Test Satellite
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
EUV	Extreme Ultraviolet

F

FAX	Facsimile
FC	False 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	Groupement pour le Développement de la Télé-détection Aérospatiale
GEO	Geostationary Earth Orbit

G (cont.)

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
<i>G/T</i>	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

H (cont.)

HRPT	High Resolution Picture Transmission
HRS(D) (S)	Hurricane Rapid Scan Day (Stereo) GOES-East and West scan every 7 1/2
Hz	Hertz formerly cycles per second

I

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

I (cont.)

ITOS	Improved TIROS Operational System
ITPR	Inferred Temperature Profile Radiometer
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector (former CCIR and IFRB)

J

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

K

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

L

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

M (cont.)

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
MTBF	Mean Time Between Failures
MTF	Modulation Transfer Function
MUX	Multiplexer
MW	Momentum Wheel Medium wave Microwave Megawatt
N	
N/S	North/South
NASA	National Aeronautics and Space Administration
NASCOM	NASA Communications Network
NASDA	National Space Development Agency
NCDC	National Climatic Data Center
NE-delta-N	Noise Equivalent Change in Radiance
NE-delta-T	Noise Equivalent Change in Temperature
NERC	National Environmental Research Council
NESDIS	National Environmental Satellite Data and Information Service
NF	Noise Figure
NHC	National Hurricane Center
NHS	National Hydrological Service

N (cont.)

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

P (cont.)

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

S

S/C	Spacecraft
S/N	Signal-to-noise ratio
S/N ₀	Signal-to-noise density ratio
S-VAS	Stretched Visible Infrared Spin Scan Radiometer Atmospheric Sounder
S-VISSR	Stretched Visible Infrared Spin Scan Radiometer
SAD	Sounder/Auxiliary Data
SAGE	Stratospheric Aerosol and Gas Experiment
SAR	Synthetic Aperture Radar, or Search and Rescue
SARSAT	Search And Rescue Satellite-Aided Tracking; see COSPAS
SATCOM	Satellite Communications
SBUV	Solar Backscatter Ultraviolet
SC/N ₀	Subcarrier-to-noise density ratio
SC/OMS	Subcommittee on Operational Meteorological Satellites
SC/OES	Subcommittee on Operational Environmental Satellites

S (cont.)

SCHOTI	Standing Conference of Heads of Training Institutions of National Meteorological Services
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Cartography
SCO	Subcarrier Oscillator
SCSMEX	South China Sea Monsoon Experiment
SDUS	Small-scale Data Utilisation Station
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SEC	Second
SEM	Space Environment Monitor
SEU	Single Event Upset
SGLS	Space Ground Link System
SIGWX	Significant Weather
SIR	Shuttle Imaging Radar
SIRS	Satellite Infrared Spectrometer
SIT	CEOS Strategic Implementation Team
SLAR	Side-looking Airborne Radar
SN	Space Network
SNR	Signal-to-Noise Ratio
SOCC	Spacecraft Operations Control Center
SOES	Subcommittee on Operational Environmental Satellites
SOLAS	International Convention for the Safety of Life at Sea
SPM	Solar Proton Monitor
SPOT	Satellite Probatoire d'Observation de la Terre
SQPSK	Staggered QPSK
SPREP	South Pacific Regional Environment Programme
SR	Scanning Radiometer
sr	Steradian
SR-IR	Scanning Radiometer-Infrared Channel
SR-VIS	Scanning Radiometer-Visible Channel
SSA	WWW System Support Activities
SSM/I	Special Sensor Microwave/Imager
SST	Sea Surface Temperature
SSU	Stratospheric Sounding Unit
STA	Science and Technology Agency
STC	Scientific and Technical Committee
Ster	Steradian
STS	Space Transportation System
SW	Short wave
SW	Switch
SWIR	Short Wave Infrared
SXI	Solar X-ray Imager
SXT	Solar X-ray Telescope (Solar-A mission)
T	
T/P	Topex/Poseidon
T/V	Thermal Vacuum

T (cont.)

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

U

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

V

VAS	VISSR Atmospheric Sounder
VCP	Voluntary Cooperation Programme
VDB	VISSR Data Base
VDUC	VAS Data Utilisation Center
VHF	Very High Frequency

V (cont.)

VIIRS	Visible Infrared Imager/Radiometer Suite (NPOESS instrument)
VIP	VAS Image Processor (with P/DU current SPS)
VIRGS	VISSR Image Registration and Gridding System
VISSR	Visible & Infrared Spin Scan Radiometer
VOS	Voluntary Observing Ship
VREC	Very High Resolution Radiometer Data Recorder
VSWR	Voltage Standing Wave Ratio
VTPR	Vertical Temperature Profile Radiometer

W

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

X

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

Y

yr	Year
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Z

Z	Common abbreviation for Greenwich Meridian Time or Universal Time
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