International Telecommunication Union

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Radiocommunication Sector of ITU

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(10/2010)

The essential role and global importance of radio spectrum use for Earth observations and for related applications

RS Series

Remote sensing systems

International
Telecommunication
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Foreword

The role of the Radiocommunication Sector is to ensure the rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services, including satellite services, and carry out studies without limit of frequency range on the basis of which Recommendations are adopted.

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***Note**: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.*

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REPORT ITU-R RS.2178

The essential role and global importance of radio spectrum use for Earth observations and for related applications

(2010)

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Summary

In a World with a growing population, more pressure on resources and increasing dependence upon global trade, communication and transportation infrastructures, together with our need to accommodate environmental changes comprising both natural and anthropogenic elements, information on changes and events likely to disrupt our access to resources or our environment is becoming even more critical. Some of these disruptions can be direct dangers to life and property over scales ranging from local to global.

Many of the systems for monitoring the phenomena causing the disruptions and the means to communicate information and warnings depend upon passive and active sensors operating at radio frequencies, and use the radio spectrum for data communications and warning distribution. With the continuing pressure upon administrations to find spectrum to accommodate new radio services and to incorporate additional operations in existing services, it is appropriate to present the value and benefits of monitoring the environment and the phenomena driving it, and its protection needs.

This Report comprises three Parts.

Part A of this Report is developed in response to Resolution 673 (WRC-07) which invites ITU-R to carry out studies on possible means to improve the recognition of the essential role and global importance of Earth observation radiocommunication applications and the knowledge and understanding of administrations regarding the utilization and benefits of these applications.

It includes an extensive overview of the use of spectrum by Earth observation radiocommunication applications. Additionally it provides a background of other related science services that play a key role related to Earth observation, noting that information or data from various science services are necessary in order to carry out and enhance studies of the Earth and its environment.

The Report describes the considerable societal weight and economic benefits of spectrum use for Earth observation and other relevant activities and, where possible, references previous studies and reports that have evaluated these impacts and benefits for the global community.

The use of spectrum by the various Earth exploration and relevant Solar radio monitoring applications has considerable societal weight and economic value. It is however still difficult to quantify these benefits to society as a whole because there are no figures for human grief and there are no simple methods to translate damage to environment into economic values; moreover, some benefits can only be evaluated or realised over very long periods of time.

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. 90% 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.

In addition to the information relevant to Resolution 673 (WRC-07), this Report provides information on other observation applications.

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[*] Throughout this text the units million, billion and trillion have the following meaning:
1 million = 1 000 000 = 1x 106 (1 Mega-).
1 billion = 1 000 000 000 = 1 x 109 (1 Giga-).
1 trillion = 1 000 000 000 000 = 1 x 1012 (1 Tera-).

Part B is an overview of solar radio monitoring applications that complements the material provided in Part A. In some cases knowledge of the solar influence upon terrestrial phenomena being studied is a key element in understanding those phenomena and their environmental and societal impacts. In other cases the programs monitor solar behaviour that can have significant impact on human activities, communications infrastructure and safety of life.

In **Part C** a description is given of benefits from spectrum use by the radio astronomy and space research. These services work in the frontline of innovation in radio technology and are as such an enabler of many technologies not only used by other radio services, including those described in Part A, but also by many non-radio applications.

Attachment 1 contains an overview of acronyms used in this Report.

PART A

Earth observation

A.1 Introduction

Information about climate, climate change, weather, precipitation, pollution or disasters is a critically important everyday issue for the global community. Earth observation activities allow to provide this information, which is required for the daily weather forecast and prediction, studies of climate change, for the protection of the environment, for economic development (transport, energy, agriculture, building construction, ...) and for safety of life and property.

One gets so used to this that one is inclined to forget that this information is either based on measurements, or gathered and distributed via radio frequency applications. However, one does consider the continuous delivery of information about the atmosphere or weather to be a routine, although a very complex one, and not “just science”, like no one does consider the operation of a mobile telecommunication system as a science.

Satellites provide the most cost-efficient, if not the only, way to monitor the environment of the entire Earth, both land, sea, and air. Unique capabilities of Earth exploration-satellite service (EESS) satellites include observing wide-areas non-intrusively and uniformly (by using the same instrument) with the ability to rapidly target any point on Earth, including remote and inhospitable places, and to continue with a series of observations over a long period of time. Through these capabilities, the EESS brings many benefits to society in both the non-profit and commercial sectors.

Radio frequencies represent scarce and key resources used by Earth observation systems to measure and collect data upon which analyses and predictions, including warnings, are based or processed. This information is disseminated to governments, policy makers, disaster management organisations, commercial interests and the general public.

On a more general basis, the utmost importance of radio spectrum for all Earth observation activities, either ground or space based, is to be stressed, in particular with regards to the global warming and climate change activities, but also for applications that are nowadays taken for granted such as the daily weather forecast and prediction.

Mankind’s influence on the atmosphere of the planet Earth has expanded in recent decades from the local scale of urban pollution to global scale effects such as the ozone hole. This is also indicated by more and more comprehensive evidence of the enhanced greenhouse effect.

Monitoring terrestrial chemical constituents is essential in the middle atmosphere corresponding to the stratosphere and the mesosphere. At altitudes higher than the tropopause (10 to 18 km from the pole to the tropics), ozone molecules play an important role by absorbing the ultraviolet (UV) radiation of the Sun, which is harmful to mankind, flora and fauna, and in general to any terrestrial life if the amplitude of the radiation reaching the ground is strong. For more than 50 years, man has imprudently used chlorofluorocarbons (Freon’s) going up into the stratosphere where they are destroyed by UV radiation, freeing large quantities of chlorine monoxide, the most dangerous destroyer of ozone molecules.

Committee on Earth science and applications from space of the U.S. National Research Council, concluded in 2007 in its publication "Earth science and applications from space: National imperatives for the next decade and beyond," as follows:

"*The world faces significant environmental challenges: shortages of clean and accessible freshwater, degradation of terrestrial and aquatic ecosystems, increases in soil erosion, changes in chemistry of the atmosphere, declines in fisheries, and the likelihood of substantial changes in climate. These changes are not isolated; they interact with each other and with natural variability in complex ways that cascade through the environment across local, regional, and global scales.*

Addressing these societal challenges requires that we confront key scientific questions related to ice sheets and sea-level change, large-scale and persistent shifts in precipitation and water availability, transcontinental air pollution, shifts in ecosystem structure and function in response to climate change, impacts of climate change on human health, and the occurrence of extreme events, such as severe storms, heat waves, earthquakes, and volcanic eruptions."

To this respect, the worldwide effort to build a *Global Earth Observation System of Systems* (GEOSS) over the next 10 years within the Group on Earth Observation (GEO) represents an essential step and is presented in this Report. Indeed, GEOSS will work with and build upon existing national, regional, and international systems to provide comprehensive, coordinated Earth observations from thousands of instruments worldwide, transforming the data they collect into vital information for our society.

The development of new, mass-market and added-value radio applications is putting increasing pressure on the frequency bands used for Earth observation purposes. This competing for spectrum presents the potential risk of limiting Earth observation 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.

In spectrum management it is becoming more and more important to estimate the value of different use of spectrum. In the case of spectrum used for Earth observations, this estimate may be quite difficult, as the benefits can relate to the society as a whole and they may be difficult to be quantified as they are realised over a very long period of time. Therefore, comparison with the benefits of services in the commercial field is often difficult and frequently leads to unbalanced conclusions.

These difficulties in evaluating and recognizing the benefits of spectrum use for Earth observation applications resulted in Resolution 673 (WRC-07) inviting ITU-R to carry out studies on possible means to improve the recognition of the essential role and global importance of Earth observation radiocommunication applications and the knowledge and understanding of administrations regarding the utilization and benefits of these applications.

Part A gives examples of attempts to quantify the economic and societal value of the use of spectrum by Earth observation applications which are obviously significant.

A.2 Earth observation radio applications and techniques

A.2.1 Overview

This Chapter gives a description of the various applications for which the spectrum is used by the Earth observation community. Table A.1 specifies the different types of radio applications use by Earth observation systems.

TABLE A.1

Different types of systems in use for Earth observation

Type of Earth observation system		
Passive applications		Satellite remote passive sensors
		Ground based passive sensors
Active applications	Ground-based radars	Weather radars and wind profilers
	Meteorological aids	Radiosondes
	Earth to space data transmission bands	Earth exploration and meteorological satellites
	Space to Earth data transmission bands	Earth Exploration and meteorological satellites
	Space based radars	Satellite remote active sensors, (altimeters, scatterometers, synthetic aperture radars, precipitation radars and cloud profile radars)

Each of these plays a key role in collectively informing about nature of the Earth, its environment and mankind's impact upon it. Therefore, although each application can be considered in isolation regarding spectrum use, the true benefit to society comes from the information gained collectively from all these applications services and the related studies. It should hence be stressed that a lack of any of this system's radio components, whether associated with measurement, collection or dissemination, is able to put at risk the Earth observation process.

The so-called "science services" use radio emissions to register naturally occurring physical phenomena or to communicate information between different locations.

Passive sensing involves the use of pure receivers, with no transmitters involved; active sensing involves transmitters and receivers, as do communications.

Table A.2 specifies the radiocommunication services considered in this Part A, and includes the reference to their definitions in the Radio Regulations (RR).

TABLE A.2

The radiocommunication services considered in Part A of this Report

RR Service	**Abbreviation**	**Definition in RR**	**Description/ applications (= not the RR definition)**
Meteorological aids service	MetAids	1.50	Meteorology, e.g. weather balloons
Earth exploration-satellite service, (active)	EESS (active)	1.51	Active remote sensing of characteristics of the Earth and its natural phenomena using space based assets and artificial sources that emit radiation, directing it towards the object of interest and collecting the return signal
--	--	--	Passive ground based observations of the atmosphere: Aeronomy
Earth exploration-satellite service, (passive)	EESS (passive)	1.51	Passive remote sensing of characteristics of the Earth and its natural phenomena using space based assets
Earth exploration-satellite service	--	1.51	EESS comprises 3 types of usage: – real time data transmitted immediately to any station in line of sight of the satellite; – feeder links between the satellite and specific Earth stations for the transfer of the stored data and the control of the satellite; – data collection platforms gathering information related to the Earth, the environment and scientific application, and sending the data to satellites .
Meteorological-satellite service	Metsat	1.52	Weather and environment observation, intended for meteorology Uplinks to satellites containing processed data enabling distribution to any station in line of sight of the satellite
Space research service	SRS	1.55	Data links to and from spacecrafts supporting science service applications
Space operation service	SOS	1.23	Telecommand and telemetry links exclusively for the operation of spacecraft
Radiolocation service	RLS	1.48	Meteorological radars and wind profilers

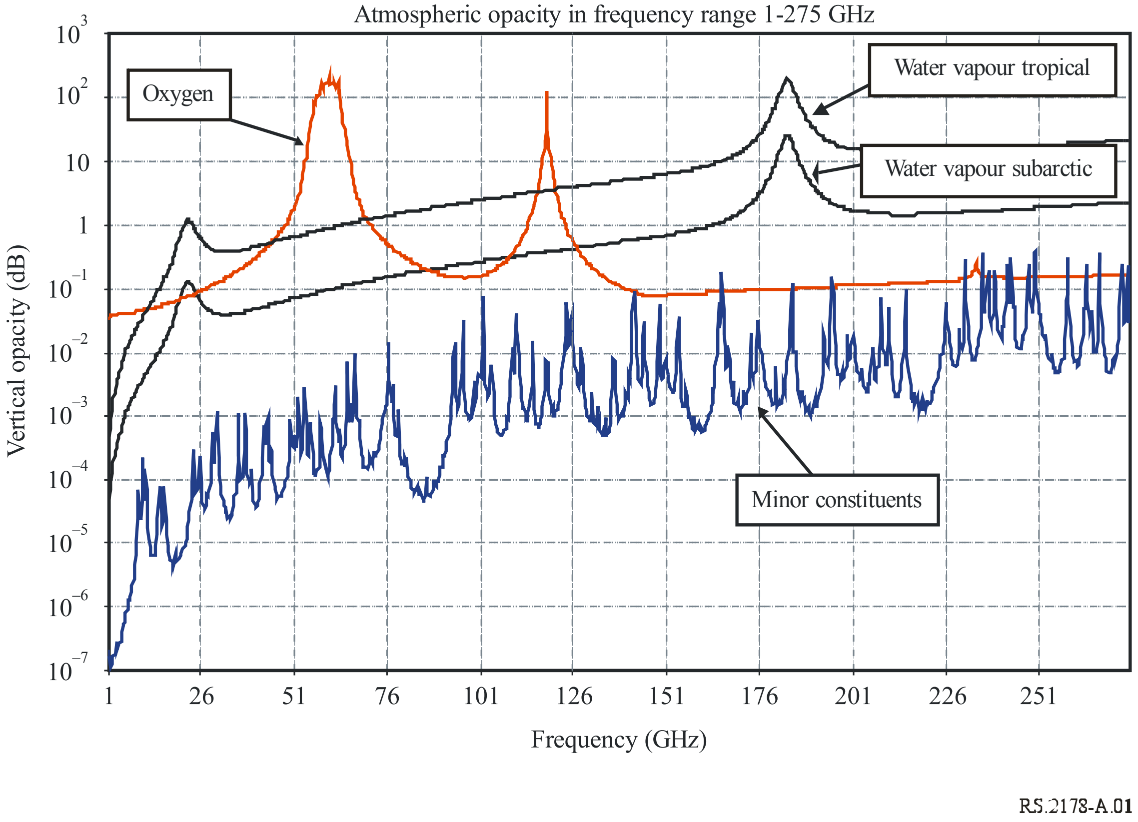
In general, these services use only a small portion of spectrum and exclusive use is exceptional. Most of the bands used by Earth observations are shared with other services. For example, on data transmission services most of the bands are shared with fixed and mobile services and Earth exploration-satellite service active sensors share bands with radionavigation and radiolocation.

A.2.2 Passive techniques

The passive observation technique (passive sensing) implies the measurement of naturally occurring radiations, usually of very low power levels, which contain essential information about the physical process under investigation; it involves the use of receive-only techniques, with no transmitters involved. All material is continually radiating electromagnetic energy; each molecule in the atmosphere or each surface has unique frequency characteristics, and therefore it can be recognized from its predetermined fixed spectral signature (see Fig. A.1). Consequently, there are no alternative spectral options available for these specific measurements and therefore these frequency bands are an important natural resource that requires protection.

FIGURE A.1

Spectral lines of natural components and their corresponding atmospheric opacity



Components in the atmosphere can be detected by radiation peaks (lines) indicating the presence of specific molecular species. The absence of power at certain frequencies indicates for example the absorption of the signals by atmospheric gases. The strength or absence of signals at particular frequencies is used to determine whether specific gases (molecules, moisture and pollutants being obvious examples) are present and if so, in what quantity and at what location.

The oxygen line is used for deriving the temperature profile of the atmosphere, similarly the water vapour line is used to derive the humidity profile.

A.2.2.1 Satellite remote passive sensors

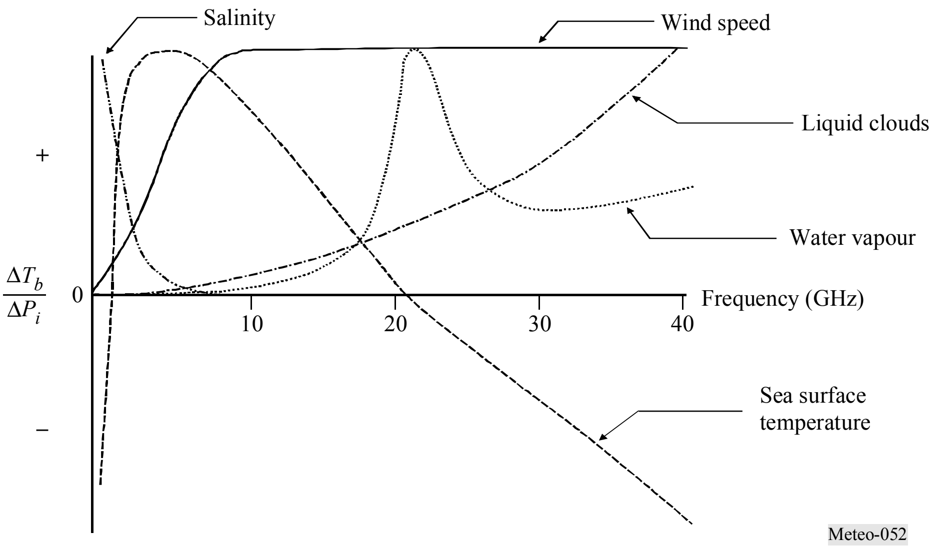
Global problems require global monitoring which is provided by sensors located onboard satellites having the possibility to scan the atmosphere at various altitudes up to 120 km. For the measurement of surface and atmosphere parameters (e.g., water vapour, sea surface temperature, wind speed and direction, 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 are generally 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 Fig. A.2 which represents the sensitivity of natural microwave emissions over ocean surfaces 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.

Signal strength at a given frequency may depend on multiple parameters, which makes it necessary to use several frequencies (or reference windows) at the same time and at the same location to match the multiple unknowns. The use of multiple frequencies is the primary technique used to measure specific characteristics of the Earth surface.

FIGURE A.2

Sensitivity of brightness temperature to geophysical parameters 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 A.2 shows 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;

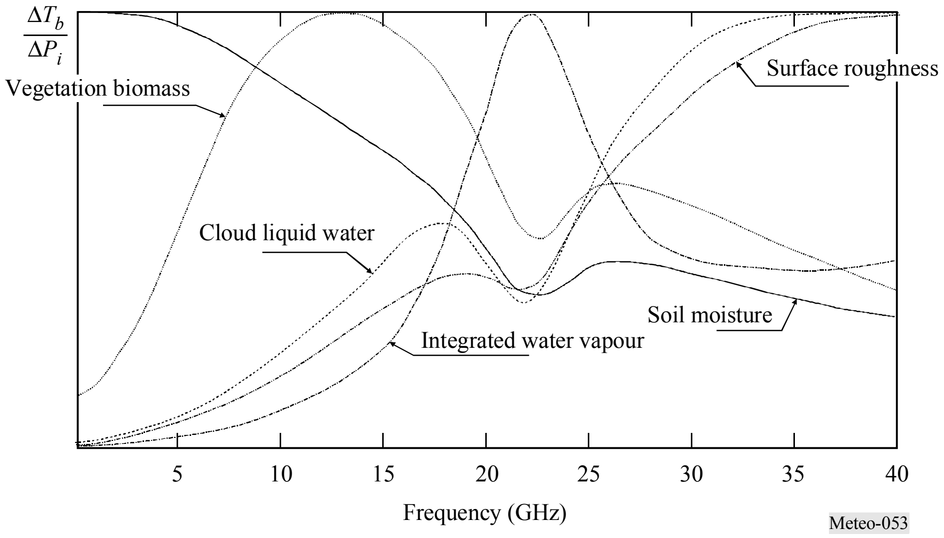
– the 17-19 GHz region, where the signature of sea surface temperature and atmospheric water vapour is the smallest, is optimal for ocean surface emissivity, which is directly linked to the wind speed near the surface, or to the presence of sea ice. Ocean surface temperature also has some sensitivity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

- total content of column water vapour can be best measured around 24 GHz, while liquid clouds are obtained via measurements around 36 GHz;
- five frequencies (around 6 GHz, 10 GHz, 18 GHz, 24 GHz and 36 GHz) are necessary for determining the dominant parameters.

The situation over land surfaces is more complex due to the variability of surface characteristics ranging from cold snow and ice cover to hot dry deserts to wet rain forests. Over land, soil moisture, vegetation biomass, water vapour, cloud liquid water, and surface roughness all contribute to the received signal (see Fig. A.3). Again, observations at multiple frequencies are needed to resolve the individual components.

FIGURE A.3

Sensitivity of brightness temperature to geophysical parameters over land



Already low levels of interference received at the input of the passive sensors may degrade passive sensor operations since, in most cases, the sensors are not able to discriminate between these natural radiations and man-made radiations. In this respect RR No. 5.340[1] offers the passive services protection to deploy and operate their systems in the more critical frequency bands. Even a little interference in a "passive" frequency band may have far-reaching impact on the overall quality and the interpretation of the measurements of global components in the Earth's atmosphere and land and ocean surfaces. It should be noted that it is very difficult to distinguish between the "wanted signal" and an interfering signal at comparable energy level.

It is to be noted that passive sensors mounted on satellites need a communication link to earth stations for data transfer (see § A.2.4).

A.2.2.2 Ground-based passive sensors

Ground-based passive sensing is done in a worldwide network composed of more than 70 high-quality, remote-sensing research stations; its objectives are observing and understanding the physical and chemical state of the stratosphere and upper troposphere and assessing the impact of stratosphere changes on the underlying troposphere and on global climate.

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[1] The RR No. 5.340 states that "All emissions are prohibited in the following bands", followed by a list of frequency bands.

This ground passive sensing activity is governed by the Network for the Detection of Atmospheric Composition Change (NDACC)[2].

The primary goal is to obtain high quality measurements of a broad range of atmospheric chemical species and parameters. The initial objective of the NDACC was to make observations through which changes in the physical and chemical state of the stratosphere could be determined and understood. While the network remains committed to monitoring changes in the stratosphere, with an emphasis on the long-term evolution of the ozone layer (its decay, likely stabilization and expected recovery), its priorities have broadened considerably to encompass:

– detecting trends in overall atmospheric composition and understanding their impacts on the stratosphere and troposphere;

– studying atmospheric composition variability at inter-annual and longer timescales;

– establishing links and feedbacks between climate change and atmospheric composition;

– calibrating and validating space-based measurements of the atmosphere;

– supporting process-focused scientific field campaigns;

– testing and improving theoretical models of the atmosphere.

The NDACC ground-based microwave radiometers are permanently operational to measure ozone, chlorine monoxide, water vapour, nitric acid, carbon monoxide and some other minor constituents, using frequencies in the range from 22 GHz to 278 GHz.

A.2.3 Active techniques

The active observation technique differs from passive sensing in that it involves both transmitters and receivers.

For satellite active sensing, a signal is transmitted and the reflected signal is usually received by the same satellite. The use of active sensing varies from measuring the characteristics of the sea surface such as wave height and winds or determining the density of trees in the rain forest.

In general, one considers five key active spaceborne sensor types:

– *Type* 1: Synthetic aperture radars (SAR) – Sensors looking to one side of the nadir track, and produce a radar image of the Earth's surface. In addition, by combining images from two positions of the satellite, using a technique called interferometric SAR, or InSAR one can develop topological elevation maps; by overlaying images taken at different times, one can measure Earth surface movements in the range of centimetres.

– *Type* 2: Altimeters – Sensors looking at nadir, measuring the precise time between a transmit event and receive event, to derive the precise altitude of the Earth's ocean surface. A new generation of altimeters will be also able to measure the accurate altitude of lakes, large rivers and open land surfaces.

– *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.

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[2] http://www.ndsc.ncep.noaa.gov.

At ground, meteorological radars operate by emitting radio signals, which are reflected by different targets being either precipitations (rain, hail, snow, …) or even in case of Doppler mode, dust, insects or solely atmospheric disturbances that are not particularly efficient reflectors.

One can distinguish two main meteorological radar types:

- The first and most familiar one is the rotating weather radar which provides precipitation and wind data within a volume which is centred on its own location.
- The wind profiler radar (WPR) which provides data from a roughly cone-shaped volume which is directly above the radar and measures wind velocity – speed and direction – as a function of height above ground as well as, if properly equipped, air temperature.

A.2.4 Data transmission

The EESS and meteorological-satellite service (MetSat) allocations are widely used according to the following needs:

- Space-to-Earth:
  - Immediate dissemination of real time data acquired by the sensors on-board EESS and MetSat satellites directly to the users.
  - Transfer by downlinks of the stored data from the satellite to dedicated earth stations. These data can be derived from the operation of passive or active sensors, as well as any kind of other sensor that records images of the Earth or the Atmosphere in the visible, infrared or ultraviolet domain.
- Earth-to-space:
  - Transfer of information recorded by data collection platforms relating to the characteristics of the Earth or any natural phenomena. The corresponding data are gathered on board dedicated satellites which then retransmit these data to dedicated earth stations.
  - Transfer of processed data to a Metsat satellite enabling distribution to any station in line-of-sight of the satellite.

One can also cite radiosondes that transmit data measured *in-situ* (typically temperature, relative humidity and wind speed) to fixed receiving stations located on the ground.

A.2.5 Space operations

The space operations service allocations, although available for satellite systems of any sort, are mainly used by space science service systems operated in the framework of EESS, MetSat and SRS for controlling and monitoring of the satellites and also for data transmissions. Thus the frequency bands allocated to space operation are of vital importance for the space science systems and constitute an indispensable component of such systems. In case of emergency situations which may occur when for example a satellite has lost its nominal altitude, satellite operators may ask the assistance of the world earth stations network of space agencies in order to recover the altitude of the lost satellite.

A.3 Application domains

A.3.1 Meteorology and climatology

Considering b) and c) of Resolution 673 (WRC-07) read as follows:

> *b)* that the collection and exchange of Earth observation data are essential for maintaining and improving the accuracy of weather forecasts that contribute to the protection of life, preservation of property and sustainable development throughout the world;

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;

Meteorology is a crucial part of everyday life and has many connections with people daily preoccupations. The weather forecast is probably the most popular programme on TV or radio today. Not only does it affect the way one dresses or decides 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.

Weather forecasting is based on continuous global measurements of the state of the atmosphere. Numerical computer models, using these data, calculate the atmospheric development for the forthcoming days. These measurements include ground-based and satellite-based active and passive observing systems.

Many countries directly assimilate microwave satellite data in their numerical models, such as those listed in Table A.3. Most of other countries not assimilating these data however receive the numerical models products to ensure their own forecasts. To this respect, they are also relying on microwave satellite data.

TABLE A.3

Countries which assimilate microwave satellite data in numerical weather models

Australia	Brazil	Canada
China	France	Germany
Italy	Japan	New Zealand
Norway	Poland	United Kingdom
United State of America		

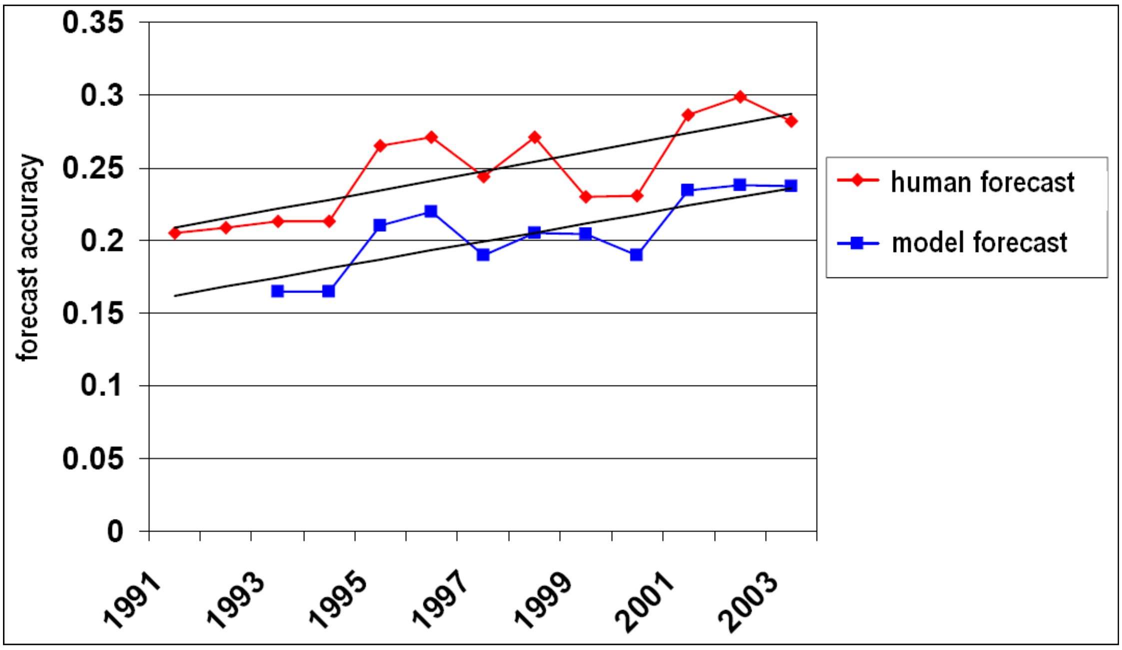
One Report indicates that, if microwave data in just one band were unavailable, the accuracy of forecasting would be set back eight years. One weather model's statistics shows, in spite of historic reliance on traditional instrumentation, that microwave data is the third most important contributor to improving the quality of weather model output.

Similarly weather forecasters rely on the weather models. In fact their forecasts improve in harmony with weather models, as Fig. A.4 shows. Since many people rely on human forecasters for weather information it follows that they, albeit unknowingly, rely on passive microwave satellite data during their everyday lives.

Under the auspices of the World Meteorological Organisation (WMO) a worldwide exchange of meteorological data takes place. Beside radio spectrum that is required for the measurements and observations, meteorology also uses radio spectrum for the transmission of observation data.

FIGURE A.4

Accuracy of forecasts made by humans and models



Radio-frequencies represent scarce and key resources for provision of meteorological services to the global community used for measurement collection and dissemination of the information. All these frequency applications are inter-related and help to comprise a global meteorological system. The Global Observing System (GOS), coordinated by WMO, comprises components which make use of a number of different radio applications and services:

– **Space-borne sensing (passive and active)** of the Earth's surface and atmosphere plays an essential and increasing important role in operational and research meteorology, in particular for mitigating the impact of weather and climate-related disasters, and in understanding, monitoring and predicting climate change and its impacts.

The impressive progress made in 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.

– **Space-borne passive sensing** for meteorological applications is performed in bands allocated to the Earth exploration-satellite (passive) and meteorological satellite services. Passive sensing requires the measurement of naturally-occurring radiations, usually of very low power levels, which contain essential information on the physical process under investigation.

Space-borne passive sensing of the Earth's surface and atmosphere is of increasing importance in operational and research meteorology. It contributes also to the understanding, monitoring and prediction of climate change and its impacts. Meteorological systems are also used to monitor changes in climate and the environment. Mankind is faced with a variety of environmental phenomena which require careful investigation and analysis. Meteorological systems gather long-term measurement data in support of studies on changes in climate and environment. (See Figs A.5, A.6 and A.7).

– **Space-borne active sensing** for meteorological and climatological processes is performed in particular by altimeters for ocean and ice studies, by scatterometers for sea surface winds, or by rain and cloud radars. It provides important information on the state of the ocean and land surfaces and atmospheric phenomena.

EESS satellites support long-term climate modelling by providing truly global input data. While satellite observations are short-term on a climatological time scale, they nonetheless provide many essential climate variables, some of which are largely dependent upon satellite observations while others are supported and enhanced by satellite observations.

Computer models derive the most likely scenarios for the development of changes in the climate. Thus, these passive and active sensing measurements are essential background information to develop climate scenario's needed for the development of national and global policies concerning global change.

– In addition, **meteorological radars** and **wind-profiler radars** perform an important part in the meteorological observation processes. Radar data are input to the numerical weather prediction models for nowcasting, short-term and medium-term forecasting. There are currently about one hundred wind-profiler radars and several hundred meteorological radars worldwide that perform precipitation and wind measurements and play a crucial role in the immediate meteorological and hydrological alert processes (see Fig. A.8). Meteorological radar networks represent the last line of defence against loss of life and property in providing the population with warnings of flash flood or severe storm events, such as in several recent dramatic cases.

Also, wind-profiler radars and wind profiles obtained through Doppler weather radars are especially useful in making observations between balloon-borne sounding.

– Meteorological aids, mainly radiosondes, are the main source of atmospheric in situ measurements with high vertical resolution (temperature, relative humidity and wind speed) to provide real time vertical atmospheric profiles that are and will remain essential for operational meteorology, including weather analysis prediction and warnings, as well as for climate monitoring. Also, these *in situ* measurements are essential for calibrating space-borne remote sensing, in particular passive.

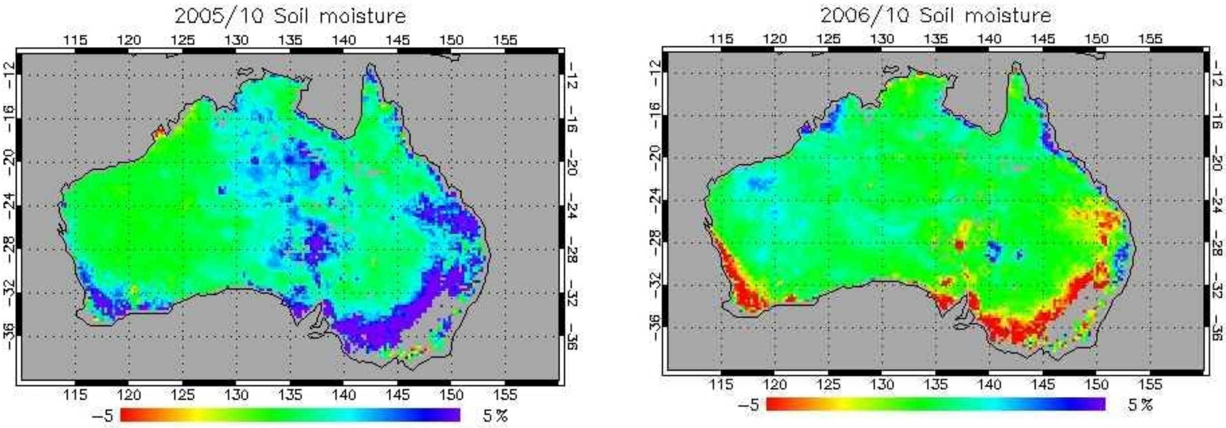
Figure A.5 shows yearly change of soil moisture distribution in Australia during October in 2005 and 2006 respectively. The National Aeronautics and Space Administration (NASA) of the United States of America acquired these data by channels of the Advanced Microwave Scanning Radiometer Earth Observing System (AMSR-E) mounted on the Aqua Satellite. Red indicates lower soil moisture, while blue indicates higher. The percentage indicated (unit of soil moisture) means the difference from averaged soil moisture for 2 years (2005-2006). It is recognized that drought occurred in south east area (Granary area) of Australia in 2006.

Figure A.6 indicates that increasing aridity is appearing in Lake Faguibine, Mali. These false-color Landsat satellite images of the lake show how it changed over the decades. The left image is made from observations acquired on January 3, 1974, and December 26, 1978. The right image is made from observations acquired on March 17, 2005, and September 28, 2006.Made with a combination of visible and infrared light, the images show vegetation as red, water as blue, and bare ground in shades of beige and gray.

Figure A.7 shows the Burma coast before and after Tropical Cyclone Nargis flooded the region. Nargis was the first cyclone of the 2008 season in the northern Indian ocean. The pair of images use a combination of visible and infrared light to make floodwaters obvious. Water is blue or nearly black, vegetation is bright green, bare ground is tan, and clouds are white or light blue. In the left image rivers and lakes are sharply defined against a backdrop of vegetation and fallow agricultural land. The right image shows the entire coastal plain flooded. Fallow agricultural areas appear to have been especially hard hit. For example, Yangôn (population over 4 million) is almost completely surrounded by floods.

FIGURE A.5

AMSR-E Measurements of drought in Australia in 2005 and 2006



Source: NASA

FIGURE A.6

Drying of Lake Faguibine, Mali

January 3, 1974, & December 26, 1978

March 17, 2005, & September 28, 2006

Source: NASA

FIGURE A.7

Cyclone Nargis Floods, (Myanmar)

April 15, 2008

May 5, 2008

Source: NASA

FIGURE A.8

Map showing European weather radars

Source: EUMETNET, the Network of European Meteorological Services

A.3.2 Disaster management

Disasters have been defined as events that result in mortality and damage which exceed the response and recovery capabilities of the affected area, creating the need for outside assistance. The meteorological aids, meteorological-satellite and Earth exploration-satellite services play a major role in activities related to disaster management: forecasting weather, detecting and tracking earthquakes, tsunamis, hurricanes, forest fires, oil leaks, etc. These services provide alerting/warning information of such disasters, they assess the damage caused by such disasters, provide information for planning relief operations, and monitor recovery from a disaster.

Space-borne observations are particularly useful when the areas are vast, the population densities low, and the technical infrastructure is vulnerable or not well developed. When in situ instrumentation or the supporting infrastructures are not in place or have been disabled by the disaster, or when the ground measurements are not accurate enough, space-borne observations can provide information helpful in alleviating the effects of disasters.

The following examples may illustrate the above:

- **Extreme weather**: Geostationary satellites provide superior temporal resolution with images available every 15-30 min and support monitoring the cloud structure, extent, and overall motion of storms. One can see where the damage has likely occurred (see Fig. A.7), and can forecast where the storm is going.
- **Floods**: Long before a flood occurs, the areas vulnerable to being flooded (areas at risk) can be identified by mapping the topology of low-lying remote areas. Land-use maps help quantify the risk by identifying populated areas. Attention can then be focused on identifying the infrastructure (roads, bridges, communications, etc.) needed to help when a flood occurs and on planning appropriate evacuation strategies.

Weather monitoring and weather forecasts can provide warnings that floods are possible or imminent. Supporting data products include areal precipitation, water equivalent from snowfall, and soil moisture, which, in combination, indicate whether the ground will absorb more rain or is already saturated.

During a flood event, imagers and synthetic aperture radars can help guide rescue workers to the specific areas affected and help assess the overall damage. The ability of SARs to penetrate clouds and provide all-weather capability is particularly useful during a flood-producing storm.

– **Coastal hazards and tsunamis**: Space-borne sensors can help identify areas at risk by locating low areas subject to flooding, or by identifying ocean bottom structure that might worsen the incoming tsunami or storm surge.

– **Drought**: The onset and progress of a drought can be observed from space by noting soil moisture, rainfall, and the distress level of the vegetation in the affected areas (see Figs A.5 and A.6). Long-range predictions of regional drought conditions can be made e.g. by tracking the Pacific ocean temperatures, which give an indication of the onset of an El Nino event, or the opposite condition, a La Niña event.

– **Earthquakes**: After a major earthquake has occurred, the sooner an accurate damage estimate is made, the sooner the appropriate rescue assets can be mobilized. Seismographs can provide a first detection of an earthquake, but interferometric SAR measurements, and in situ measurements using ground receivers of Global Navigation Satellite Systems (GNSSs) provide more accurate means of determining the location and the extent of the rupture for use in estimating the damage.

Usually the ground movements (see also Part C of this Report) associated with earthquakes are too small to appear in satellite visible or infra-red imagery. However, visual imagery can be very useful in assessing the damage caused by an earthquake and in guiding rescue efforts (see Fig. A.9).

– **Landslides, subsidence and avalanches**: Areas vulnerable to landslide activity can be identified using elevation models from SAR measurements. In this case, the slopes rather than the elevations are used. When subtle ground movement is suspected, InSAR and in situ GNSS units can provide accurate measurements.

When soil on steep hillsides becomes saturated with water during a very heavy rainfall, it becomes vulnerable to producing landslides. Thus, forecasts of heavy rainfall, particularly when coupled with knowledge of the pre-rainfall soil moisture, can provide warnings that landslides may occur.

After a landslide has occurred, InSAR images can provide an accurate mapping of the ground movement (subsidence) by comparing before and after SAR imagery of the bare Earth. Other imagery can show the areas affected by the impact on the vegetation and other surface features.

– **Volcanoes**: Since volcanic activity is frequently preceded by swelling/uplifting of the ground in the immediate area, potential volcanic activity can be monitored, to some degree, by mapping such ground movements. In situ GNSS units can provide local monitoring while InSAR observations measuring motions on the order of centimetres can provide more frequent measurements at remote locations.

Such subtle ground motions can be used to identify potential volcanic hazards anywhere in the world.

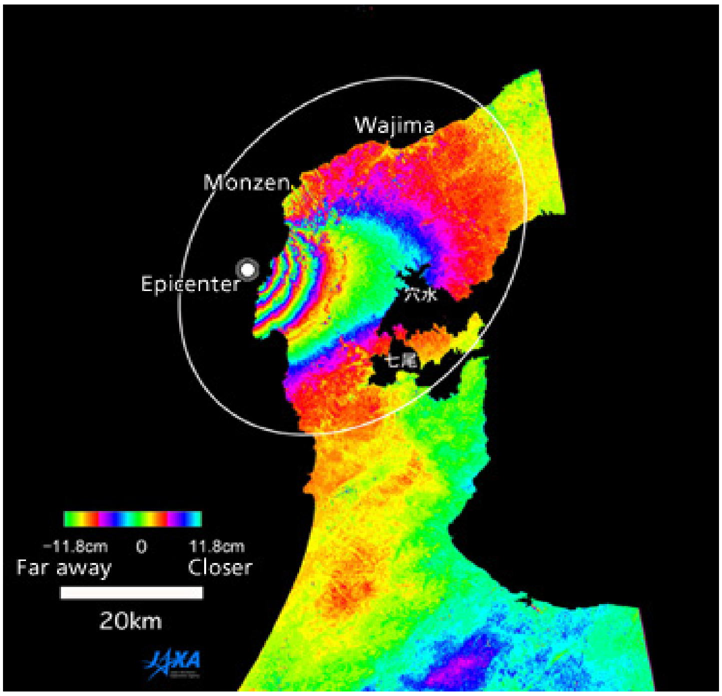
During and after an eruption, the thermal signature of the lava, ash, and hot gases are routinely tracked using infrared and visual observations from space. In particular, the volcanic ash in the atmosphere poses serious hazards to aircraft in flight.

– **Oceanic pollution**: Oceanic oil spills can be detected using SAR imagery. Operationally, oceanic oil spill detections are treated as preliminary observations and are immediately confirmed via seaborne, in-situ measurements. This technique allows large areas to be monitored at lower cost. After an oil spill is confirmed in situ, the area affected can be monitored and tracked by satellite.

Natural oceanic pollution in the form of a "red tide" (a common name for an algal bloom, associated with the production of natural toxins, depletion of dissolved oxygen or other harmful conditions) can be detected and monitored from space by observing ocean colour. Identifying and quarantining areas afflicted by a red tide protect human health. Other pollution forms (e.g. water pollutants, coastal sediments) can be detected using satellite images in the visible and/or infra-red spectrum.

FIGURE A.9

Palsar measurements of change of land surface before and after earthquake in Noto peninsula of Japan on March 25, 2007



Source: PALSAR via Japan Aerospace Explo ration Agency (JAXA)
see at: http://www.jaxa.jp/press/2007/04/20070412_daichi_e.html.

– **Sea and lake ice**: Satellite-borne passive microwave sensors have mapped sea ice extent for decades, and SARs are used operationally to guide arctic and high latitude lake shipping and to extend the shipping season at high latitudes.

– **Wildfires**: The risk for wildfires in remote, sparsely populated areas can be estimated from space measurements of soil moisture and vegetative state (i.e. is the vegetation healthy or distressed/parched?).

Wildfires can be detected using certain infrared channels being flown on spaceborne imaging instruments. These channels effectively penetrate the smoke and haze which obscure visible-wavelength observations.

> These images are useful in combating wildfires as they can be used to guide fire-fighters, and they are particularly useful in remote, unpopulated areas.
>
> After a fire has been extinguished, satellite visible and infrared imagery and SAR imagery can be used to determine the extent of the damage and to monitor the recovery of the vegetation.

Regardless of the type of disaster, the extent of the damage can be determined using moderate- and high-resolution visible/infrared imagery from satellite-borne instruments. Lower resolution SAR imagery, which is unaffected by cloud cover, can also be used to show the areas affected. The ability of SARs to penetrate clouds and provide all-weather capability is particularly useful in cloud-prone areas such as central Africa, the Amazon, and island areas such as Indonesia.

A.3.3 Other satellite imaging applications

The past decade has seen increasing public concern about the Earth, its environment and mankind's impact upon it. Global threats such as climate change and global warming, stratospheric ozone depletion, troposphere pollution and increasing number of extreme weather events, caused more concerns than ever about the need to monitor and understand what is going on in the Earth's environment. There are many aspects of the complex evolving Earth system that are still not understood.

These concerns have led to the establishment of international programme concepts, including both space- and surface-based systems, to measure on a routine basis all major elements of the global climate system.

Some of the earliest initiatives, including Meteosat, Landsat and SPOT, have already developed into long-term applications programmes integrated into regular operational use. For example, the fleet of geostationary Meteosat satellites that is observing the weather in real-time is providing a reliable stream of data ever since the launch of the first Meteosat in 1977, helping to significantly improve weather forecasting.

Earth observation from space using microwave remote sensing is a critical tool in this task because of the all-weather/day-night capabilities, unique view and high revisit rate that it provides. Remote Sensing satellites such as ERS-1,-2, Odin, Radar-Sat, ADEOS, ALOS, Resours, Topex-Poseidon, IRS, MOS, ERS, CBERS, METOP, FY-3 and ENVISAT carrying a multitude of instruments have made major contributions in areas as diverse as global and regional:

- ocean observations;
- atmospheric composition and chemistry;
- sea ice monitoring;
- glaciology and snow cover investigations;
- land cover monitoring;
- investigations into the dynamics of the Earth's crust (seismology and volcanology).

Active remote sensing in the microwave region offers several advantages over visible region sensors and passive microwave sensors. Besides being uniquely sensitive to several land/ocean/atmosphere variables (e.g. plant moisture and cloud height), active sensing can, for instance, penetrate the surface and vegetation and operate on an all-weather and day/night basis.

For most of the EESS (active) sensors, the operating frequency range is linked to the geophysical parameters to be observed. For instance, to enable measurement of clouds and precipitation, higher frequencies are used to carry out measurements in the upper atmosphere, whilst lower frequencies have to be used for measurements in the lower atmosphere. Furthermore sufficient bandwidth is required to get the proper spatial resolution and measurement accuracy.

To illustrate one of the applications, Fig. A.10 shows an artificially coloured ERS-1 SAR image, covering an area of 75 km x 75 km. It shows the Teles Pires river in Brazil and a regular pattern of deforestation is clearly visible in the rectangular patches of destroyed forest extending over areas as large as 20 km. More recently, spaceborne SAR imagery was used to detect illegal logging activities in Indonesia after which action was taken to arrest and detain the responsible persons.

FIGURE A.10

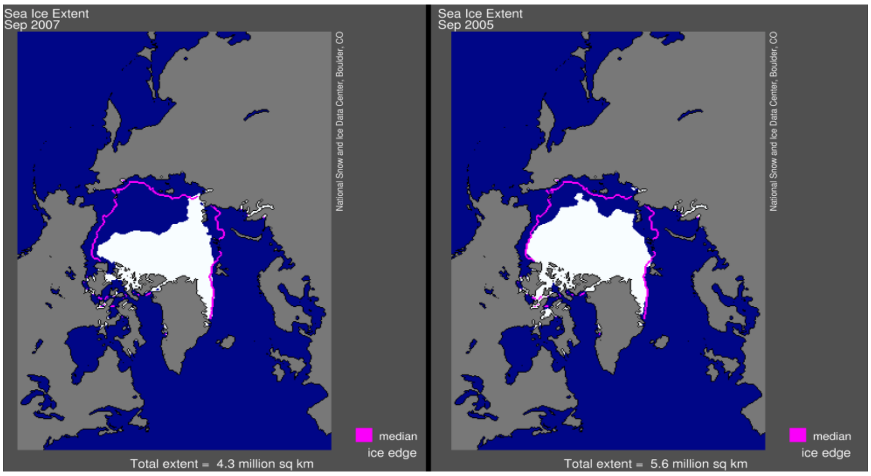
Brazil Deforestation

Source: European Space Agency (ESA), 1992

The microwave radiometric measurements along with other measurements (e.g. infrared) are converted to data file products such as rain rate, sea surface temperature, soil moisture or sea ice cover. Products can be categorized by the media they describe such as the atmosphere, ocean or land. The most critical and well known products are forecasts of weather and climate. These forecasts affect human endeavours. These products include: hurricane formation and path displays, atmospheric temperature profiles, and water precipitation maps.

FIGURE A.11

Changes in sea ice concentration 2005-2007



Source: National Snow and Ice Data Center (NSIDC)

Figure A.11 shows the diminished sea ice concentration around the north pole.

The EESS operates passive sensors that are designed to receive and measure natural emissions produced by the Earth surface and its atmosphere. The frequency and the strength of these natural emissions characterize the type and the status of a number of important geophysical, atmospheric and surface parameters (land, sea, and ice caps), which describe the status of the Earth/atmosphere/oceans system, and its mechanisms:

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

– three-dimensional atmospheric parameters such as temperature profiles, humidity profiles, total water vapour content and concentration profiles of radioactively and chemically important trace gases (for instance ozone and chlorine monoxide).

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

Considering d) and e) of Resolution 673 (WRC-07) read as follows:

> *d)* that Earth observations are also used to obtain pertinent data regarding natural resources, this being particularly crucial for the benefit of developing countries;
>
> *e)* that Earth observations are performed for the benefit of the whole international community and all mankind, are shared among all countries and are generally available at no cost,

The main goal of the Earth exploration-satellite service (EESS) is, in addition to the meteorological and climatological activities described in § A.3.1, to monitor the changes of the Earth and of the atmosphere.

Observations of the Earth's atmosphere, land areas, and oceans have become increasingly important in understanding Earth as a system. Examples of environmental data which can be provided by the EESS are the following:

– **Water**: The EESS provides the means of monitoring the global water supply, both globally and locally. Imaging and radar techniques provide a means of monitoring the height of lakes. Snow depth can be monitored by techniques using microwave instruments; snow depth in turn allows forecasts of water supplies. Observed rainfall and weather predictions also provide useful if not necessary input to water resource managers.

– **Ecosystems**: Globally, ecosystems are under stress from land-use change, pollution, and overexploitation of natural resources. Ecosystem conditions and trends can be followed using satellite observed leaf area indices, primary-production indices, and energy-water exchange combined with topography, land usage/land change, geology, soil data, and climate data.

– **Agriculture**: The EESS supports improving agriculture in many ways. The most obvious use is in providing better weather forecasts to help farmers plan their seeding and harvest operations. Further, satellite observations support drought predictions, sometimes far enough in advance for farmers to plan accordingly.

Satellite imagery is used to monitor crop health on a global scale by observing soil moisture, leaf index, vegetation indices, rainfall. The onset of crop failures leading to famines can be monitored and appropriate resources brought to help. On occasion, satellite observations of a relatively nearby bumper crop have led to more timely and cost effective relief operations.

Weather forecasts and crop health observations combine to help farmers plan the optimum harvest time.

– **Biodiversity**: The mission of the Global Biodiversity Information Network is to monitor and model the ways in which species and ecosystems respond to climate change. While measuring and monitoring species is generally impractical from space-base platforms, biodiversity data can be combined with climate, weather, and habitat (ecosystem) data provided from such platforms. EESS remote sensing systems have some capability to identify ecosystems that are unique or highly diverse and support migratory, endemic, or threatened species. Further, by monitoring such ecosystems, EESS resources can help identify threats in time for protective action to be taken. One such threat is the fragmentation of ecosystems due to human encroachment through urban and transport development.

– **Human factors**: Many human factors affecting the environment can be observed from space. Population distributions have been mapped using night time lighting from population centres and using road networks, slopes, and land cover as corollary data, most observable from space. Much, if not most, of the Earth's human population now live in urban areas. These urban areas can be identified and characterized from space. Their growth can be monitored and the impacts of such growth can be predicted and planned using ecological data regarding the surrounding area.

Currently various operational satellite instruments (e.g. AMSU-A, MHS, AMSR-E, MTVZA-OK,) provide key meteorological data. Future remote sensing satellites (following series of ESA’s MetOp satellite and National Oceanic and Atmospheric Administration (NOAA) instruments EOS AQUA, GCOM-W1, SICH-1M, Megha-Tropiques, SMOS) will provide information about water on a global basis and about rainfall amounts and patterns.

Current and future missions are aiming at understanding the Earth’s environment by improving the measurements of atmospheric temperature, water vapour and precipitation, land surface monitoring such as soil moisture, sea ice monitoring and glaciology, stratospheric ozone depletion, middle atmosphere chemistry, tropospheric pollution, and sea-surface temperature and salinity.

A.4 Essential benefits of Earth observation

A.4.1 The Group on Earth Observation (GEO)

More and more, citizens require their governments to make evidence-based policy decisions about the environment, including better predictions of natural disasters, epidemics, the impact of energy choices, or variations in the climate.

Increasing concerns about environmental change have been raised at intergovernmental conferences (such as the Kyoto climate conference) and have led to the establishment of international programme’s such as the Group on Earth Observations (GEO) and Global Monitoring of the Environment and Safety (GMES).

One can improve prediction of the Earth system only through comprehensive, systematic Earth observation. Observing what is happening today and analyzing what has happened in the past, is the key to understanding and predicting what will happen in the future.

"*Prediction is a difficult art when addressing the complexity of Earth processes ... how do we account for phenomena as diverse and poorly understood as seismic fault dynamics, climate variation, or the ecological intricacy of a wetland? Observations are the only means for deciphering nature's complexities." (José Achache, GEO Secretariat Director).*

The **Group on Earth Observations** (GEO) is an intergovernmental body currently comprising, as of September 2009, 80 member countries, the European Commission and more than 58 participating international organisations. On the basis of a 10-Year Implementation Plan for the period 2005 to 2015, GEO is leading a worldwide effort to build a Global Earth Observation System of Systems (GEOSS). This GEOSS will work with and build upon existing national, regional, and international systems to provide comprehensive, coordinated Earth observations from thousands of instruments worldwide, transforming the data they collect into vital information for society.

The following summits led to the creation of GEO and GEOSS:

- The **World Summit on Sustainable Development**, Johannesburg, 2002, highlighted the urgent need for coordinated observations relating to the state of the Earth.
- A **meeting of the Heads of State** of the Group of 8 Industrialized Countries Summit in June 2003 in Evian, France, affirmed the importance of Earth observation as a priority activity.
- The **First Earth Observation Summit** was convened in Washington, D.C., in July 2003, and adopted a Declaration establishing the ad hoc intergovernmental Group on Earth Observations (ad hoc GEO) to draft a 10-Year Implementation Plan.
- The **Second Earth Observation Summit** in Tokyo, in April 2004 adopted a Framework Document defining the scope and intent of a Global Earth Observation System of Systems (GEOSS).
- The **Third Earth Observation Summit**, held in Brussels in February 2005, endorsed the GEOSS 10-Year Implementation Plan and established the intergovernmental Group on Earth Observations (GEO) to carry out this plan.

GEOSS will provide comprehensive and coordinated observations that will be transformed into vital information for society and mankind, related to safety-of-life, societal, development or economical interest in a large number of domains yielding to a broad range of societal benefits (see also Fig. A.12):

- Reducing loss of life and property from natural and human-induced **disasters**.
- Understanding environmental factors affecting human **health** and well-being.
- Improving management of **energy** resources.
- Understanding, assessing, predicting, mitigating, and adapting to **climate** variability and change.
- Improving **water** resource management through better understanding of the water cycle.
- Improving **weather** information, forecasting and warning.
- Improving the management and protection of terrestrial, coastal and marine **ecosystems**.
- Supporting sustainable **agriculture** and combating desertification.
- Understanding, monitoring and conserving **biodiversity**.

From the initialization of GEO, radio frequency protection has been recognized as a critically important issue for Earth observations, in particular in frequency bands where passive sensing measurements are performed, and early in the development of the GEOSS 10-Year Implementation Plan, the *ad hoc* GEO subgroup on data utilisation stressed a specific goal of the GEOSS initiative to ensure that these radio frequencies are protected.

The essential and important role of the GEOSS was clearly stressed at the Earth Observation Ministerial Summit (Cape Town, November 2007) in the so-called "Cape Town Declaration" (see Annex 3), raising in particular the necessity to ensure availability and protection of radio frequencies and welcoming, to this respect, the adoption of Resolution 673 (WRC-07), (see also § A.5: Status of radio spectrum used by science services).

FIGURE A.12

Conceptual architecture of the Global Earth Observing System of Systems (GEOSS)

A.4.2 Economic and societal value

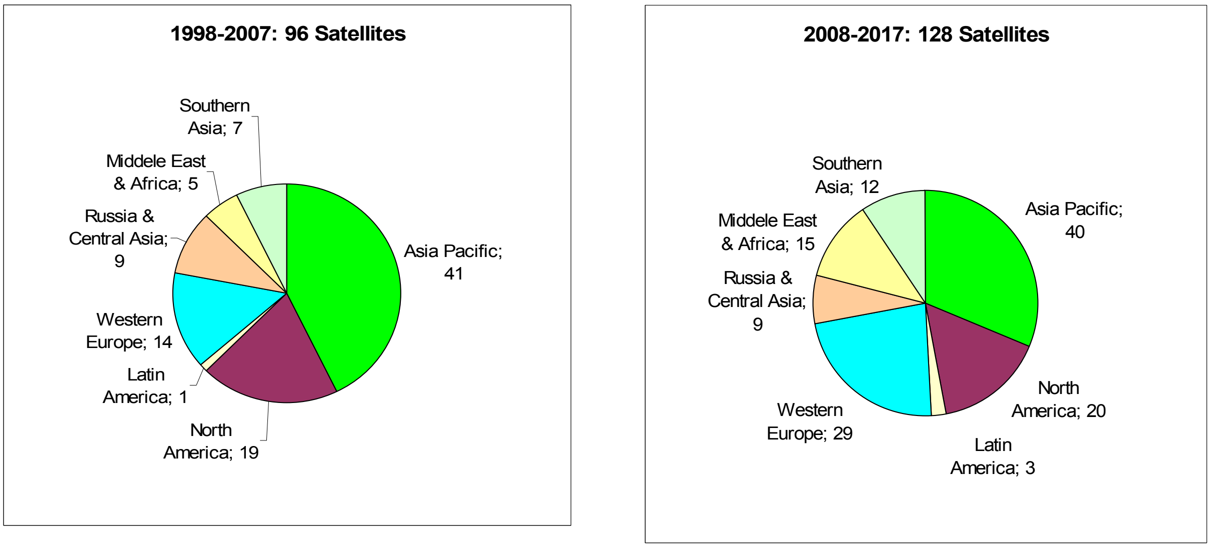
In spectrum management it is becoming increasingly important to estimate the societal and economic value of different usage of spectrum. In the case of Earth observation use of spectrum it might not be as straightforward as simply weighing up the quantified costs and benefits when considering alternative usage. This is because it is very difficult to quantify the benefits of Earth observation use: they can relate to the society as a whole, may be difficult to foresee and may be realised over a very long period of time.

Several countries around the world have made major investments in the use of spectrum for Earth observation purposes.

The Euroconsult study: "Government Space markets, World Prospects to 2017" specifies that Earth observation is the number one satellite-based application worldwide, with governments spending 6.7 billion US $ in 2008, i.e. 20% of government non-classified investment in space. Lower cost satellites and ability to address local issues have made Earth observation the top priority application for a number of countries, particularly emerging space programs. Strong growth is expected to continue in civil programs, (see Fig. A.13). 24 administrations have launched Earth observation satellite capacity.

FIGURE A.13

Breakdown of Earth observation satellites by region



Source: Euroconsult

As a return on those investments, Earth remote sensing has, over the past half century, made fundamental new discoveries and has brought us closer to understanding both the nature of the universe and our immediate environment. Sustaining these discoveries and allowing for new important discoveries will obviously require protection of the radio spectrum granted to the Earth Observations applications.

This Chapter gives an indication of the significant economic and societal returns of Earth observation and related use of spectrum.

A.4.3 Economic and societal impact of disasters

A.4.3.1 Summary

Concerning natural disasters the WMO states, amongst others, that: “The economic impacts of natural disasters have worsened over the past few decades”.

The Global Resource Information Database maintained by the United Nations Environment Programme states that:

- 118 million people are exposed each year to major earthquakes (i.e. above 5.5 on the Richter Scale);
- 343.6 million to tropical cyclones;
- 521 million are exposed to floods and 130 million to meteorological drought; and
- 2.3 million people are exposed annually to landslides.

Data from the International Federation of Red Cross and Red Crescent Societies[3] as well as the Centre for Research on Epidemiology of Disasters indicate, during the period 1998-2007, a total of 7 100 disasters, 3 900 of these being natural and 3 200 being technological.

---

[3] Annex 1 to the World Disaster Report 2008 of the International Federation of Red Cross and Red Crescent Organisations.

From the 3 900 natural disasters, about 90% (3 550) are weather and climate related and about 10% (350) have geophysical origin.

During this period 1998-2007, natural disasters worldwide have affected over 2.8 billion people and killed 1 035 000 people with a maximum of 242 000 in 2004 and a minimum of 16 700 in 2007; for technological disasters the number of people reported killed is 98 000 over these 10 years.

The total amount of disaster estimated damage during this period 1998-2007 was 804 billion US $ for hydro-meteorological disasters, 148 billion US $ for geophysical disasters and 14 billion US $ for technological disasters, (all 2007 prices).

A.4.3.2 Some detailed examples

The few examples given below specify the losses of life and damage caused by some identified disasters. It should be noted that any early warning for potential disaster will reduce these horrible consequences (see § A.4.5).

– **Coastal hazards/tsunami**: Following a 9.0 magnitude earthquake off the coast of Sumatra, a massive tsunami and tremors struck Indonesia and southern Thailand on 26th December 2004, killing over 104,000 people in Indonesia and over 5,000 in Thailand. Medium and high resolution optical images of the Aceh Province in Indonesia taken before and after the tsunami of 26 December 2004 by low Earth orbiting satellites provided authorities information for an assessment of the damage.

– **Drought**: The onset and progress of a drought can be observed from space by noting soil moisture, rainfall, and the distress level of the vegetation in the affected areas.

By the end of May 2008, millions faced hunger in eastern Ethiopia as crops failed and food prices soared, said the United Nations Children’s Fund (UNICEF). Two successive seasons of poor rains left eastern Ethiopia in drought. Ethiopia presents a picture of contrasts. While the eastern half of the country withered in drought, western crop areas received ample rain and thrived. The drought limited the production of both food and cash crops like coffee, said the Famine Early Warning System Network. UNICEF estimated that 3.4 million people would need food aid in June, July, and August as crops continue to fail.

– **Oceanic pollution**: On 11 August 2006, the oil tanker Solar sunk off the coast of Guimaras Island in the Philippines. By 24 August 2006, some 50 000 gallons of oil had leaked into the sea, polluting more than 300 km of coastline and threatening fishing as well as other islands of the Philippines. The SAR on the ENVISAT satellite was used to derive an image showing the exact location and the extension of the oil slick on 24 August 2006. The oil spill affected about 27.000 people, contaminated fishing grounds, and devastated the island’s rich marine life and tourist sites. These people received a compensation of about P 900 million (about 18 million US $).

– **Earthquake**: The earthquake in Sechuan, China, 12 May 2008, took the life of about 70.000 people, and 5 million people lost their homes. 3 400 schools had to be rebuild, 2 600 braced. The total damage is estimated to be about 100 billion Euros.

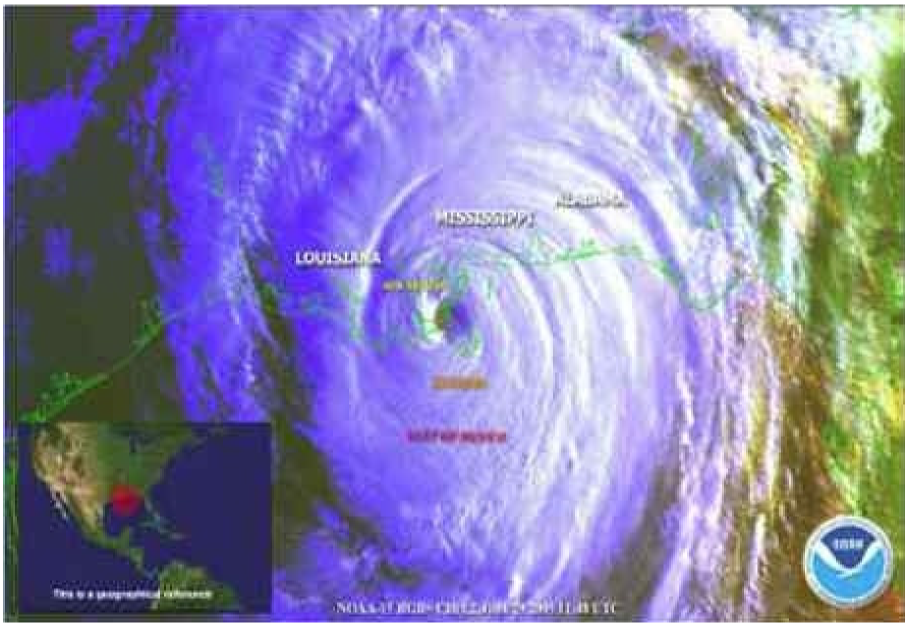
– **Wildfires**: Wildfires were rampant in the Australian summer of 2002-2003, with over 50 separate fires in the southeast portion of the continent. The capital city of Canberra was threatened by a bush fire that began on January 18th in the Namadgi National Park. Within a few days, the fires had spread to the outskirts of the city, forcing thousands of people to evacuate the city and prompting thousands more to volunteer as fire-fighters to protect Canberra from the flames. By the time the fire was under control, 4 people had died and 419 homes had been destroyed.

The Victorian (Australia) fires in February 2009 killed more then 200 people and caused damage of more than 300 million AU$ (~ 150 M€ or 200 MUS $).

– **Hurricanes**: Hurricane Katrina, 2005, (see Fig. A.14) was the costliest, as well as one of the five deadliest, in the history of the United States. It formed itself over the Bahamas on August 23, 2005, crossed southern Florida as a moderate category 1 hurricane, causing some deaths and flooding there before strengthening rapidly in the Gulf of Mexico. The storm made its second landfall as a category 3 storm on August 29 in southeast Louisiana, causing severe destruction along the Gulf coast. The most severe loss of life and property damage occurred in New Orleans. The number of fatalities reported are: 1 836 confirmed, and 705 missing. The total damage, 2008 estimation, is about 90 billion US $.

FIGURE A.14

This NOAA satellite photo shows the landfall of Hurricane Katrina on the south-eastern Louisiana coastline, August 29, 2005



A.4.4 Public investments in Earth observation

The facilities used by the Earth observation applications represent hundreds of billions of Euros/Dollars of public investments on national or international basis. This includes the building of scientific or meteorological spacecraft and the deployment of scientific or meteorological and climatological stations/networks all over the world, for which industry is an important stakeholder.

On a general basis, costs for a single passive sensor instrument for meteorology or Earth observation (both active and passive) can easily be in excess of 100 millions Euros. These costs are very often driven by the need to achieve front-line state-of-the-art system performance by means of completely innovative technical developments (including research). Because these instruments define the state-of-the-art, most are by their nature their own prototypes. The construction of these sensor instruments is very labour-intensive and requires specialized hardware.

The United States of America plans to invest over 7 billion US $ in the National Polar-orbiting Operational Environmental Satellite System (NPOESS) to fulfil identified operational and climate-monitoring needs. The NPOESS is designed to monitor global environmental conditions and collect data related to weather, atmosphere, oceans, land and near-space environment.

The EU, in cooperation with ESA, started the Global Monitoring for Environment and Security initiative (GMES). Aiming at an operational system in a few years time, GMES is now being developed using EU Framework Programme funding. GMES should establish a network infrastructure all across Europe to facilitate information gathering for a wide variety of purposes. GMES is seen as the European contribution to GEOSS. The investments into the first segment of GMES will be around 2.5 billion Euros.

According to Euroconsult European governmental investments in civil Earth observation projects in 2008 are estimated to be around 1.4 billion US $. The turnover of European space industry related to Earth observation was 825 million Euros in 2007 (provided by European Space Policy Institute).

In Europe significant investments are made to carry out operational meteorology and climate monitoring through EUMETSAT, an intergovernmental European Organisation for the Exploitation of Meteorological Satellites.

For the current generation of geostationary meteorological satellite system (Meteosat Second Generation), which is the primary European source of geostationary observations over Europe and Africa and key contribution to the Global Observing System of the World Meteorological Organization, the costs for development and operation of this system are in the order of 2 billion Euros.

For the EUMETSAT Polar System (EPS), Europe’s first polar orbiting satellite system for operational meteorology and climate monitoring, and the European contribution to the Initial Joint Polar-Orbiting Operational Satellite System in cooperation with the US, the investments in Europe are in the order of 2.2 billion Euros.

For the currently planned next generation geostationary meteorological satellite system (Meteosat Third Generation), the investments in Europe for development and operation will be in the order of 2.8 billion Euros. The investments in Europe for development and operation of the next generation polar orbiting meteorological and climate monitoring satellite system (Post-EPS) are expected also be in excess of 2 billion Euros.

A.4.5 Benefits of spectrum use for Earth observation

A.4.5.1 Disaster management

The UK Natural Hazard Working Group issued in June 2005 a Report on “The role of science in physical natural hazard assessment”. This Report recognises the high value of science services in mitigating natural hazard and is now one of the reference documents of the “Group on Earth Observation” program.

This Report highlighted in particular information from the World Bank that, during the 90’s, an efficient warning system could have decreased the economic impact of natural disasters by 240 billions US $ and that it is reasonable to assume that the cost-effectiveness of anticipatory measures will apply at least as much to catastrophes of global extent as to local natural disasters.

This Report states that “*The cost effectiveness of spending to mitigate economic losses is an important part of the argument for taking action on preparedness and mitigation, including early warning. However other potential consequences of a global catastrophe are manifold and incommensurable in economic terms, from large losses of life to threats to socio-political stability and security. We are faced with a stark choice when it comes to dealing with global geophysical events. Either take no action and incur the risks – potentially trillions of dollars of economic losses and millions of lives lost – or exercise precaution in the face of scientifically established global threats and take practicable measures to mitigate their impact.*”

The above statement highlights the importance and long term cost effectiveness of the retaining necessary access and provision of spectrum necessary for monitoring systems to operate effectively and where possible mitigate some of the economic and social impact of global and local natural disasters.

A.4.5.2 Monitoring climate change

Global Climate Change is an important item on the international political agenda. The Kyoto protocol now being ratified, the yearly Conference of the Parties of the UN Framework Convention on Climate Change continues to give worldwide political guidance. In the Report "ITU and Climate Change" Dr H. Touré, Secretary General of the ITU, states:

> "*As the specialized agency of the United Nations responsible for telecommunications/ICTs, ITU is committed to working with other organizations in combating climate change*".

Based on inventories and recommendations developed by WMO's Global Climate Observing System, parties are urged to implement climate monitoring systems that are essential to improve our understanding of climate change.

One can also note that ITU and GEO have recently agreed on a Memorandum of Understanding on "Cooperation in Earth Observations, Emergencies, and Other Matters on Mutual Interest in Information and Communications Technology".

A.4.5.3 Benefits of Earth observation systems

Irving Leveson describes benefits in his Report about the NPOESS Economic Benefits as follows: "*Economic benefits are defined to include a broad set of both monetary and social benefits. Social benefits encompass the value of such factors as improvements in health and safety, reduction in deaths, savings in household's time and improvements in the environment. Social benefits can be very large, but difficult to quantify*".

Observations of the atmosphere, land areas and oceans have become increasingly important in understanding the Earth as a system. Currently operating satellites provide key meteorological data. Remote sensing satellites provide information about water on a global basis and about rainfall amounts and patterns. Current and future missions are expected to improve measurements of atmospheric temperature, water vapour, precipitation, soil moisture, concentrations of ozone and other trace gases, sea-surface temperature and salinity.

These multiyear multi-billion-dollar missions are international in scope, reflecting the interest of many countries in obtaining accurate meteorological, hydrological, and oceanographic data as well as measurements of land-surface features and trace gases in the atmosphere. It is therefore for the benefit of the whole global community, that a better understanding is achieved of the Earth and its environment and the impact this may have globally and locally to each administration concerned.

Applications which are derived from satellite remote sensing include:

- Hurricane monitoring
- Rice production in India
- Desert expansion in China
- Sea ice concentration
- Hydrological products (rainfall, water vapour, snow cover)
- Tracking ocean circulation patterns
- Extreme event forecasting
- Study of Earth's water cycle
- Global warming models

- Crop yield forecasting
- Identification of potential famine areas
- Drought analysis
- Irrigation planning
- Flood protection
- Forest fire protection
- Monitoring of areas prone to erosion and desertification
- Initialization of numerical weather prediction models.

Direct economic and societal benefits can be associated with general benefits deriving from these missions.

In the United States of America, the costs of severe weather events alone are often in the hundreds of millions of dollars per event (see Fig. A.14). NOAA's National Weather Service forecasts, warnings, and the associated emergency responses result in a 3 billion US $ savings in a typical hurricane season. The benefit studies for the NPOESS assumed that adverse weather and short term climate impacts on the economy as estimated by the model can be reduced by 10% by the availability of forecasts, warnings and information before, during and after weather events.

The website (http://economics.noaa.gov) gives examples of economic benefits, such as:

- The potential benefit of improved data from the Geostationary Operational Environment Satellite – R series (GOES-R) will result in "more accurate temperature forecasts contributing to improved energy demand expectations and savings in the electricity and natural gas sectors" valued at 512 million US $ in 2015 and 2.56 billion US $ from 2015-2027.
- Enhanced NOAA satellite imager and sounder to improve short-term (3 h) temperature forecasts: US $ 9 million/year derived from improvements in frost mitigation.
- Improved precipitation and temperature forecasts: optimal use of forecast gives additional value of US $ 1 040 – US $ 1156 /hectare/year.
- NOAA El Niño's forecast provides economic benefits to US agriculture (by altering planting decisions) that have been estimated at US $ 265-300 million/year.
- NOAA forecasting in reducing the length of the coastline under hurricane warning saves at least US $ 640,000 per mile in costs of evacuations, etc. This has been cited in various sources, but the calculations of per mile evacuation costs are highly variable, with Reports in the literature varying from under US $ 100,000 to US $ 1 million.

However, much more important than financial savings are the savings in lives.

A further illustration of the value of meteorology has been given by the WMO[4]: "Studies in the United States of America have shown that the value of improved seasonal weather forecasts to farming in the south-eastern quarter of the country alone amounts to some US $ 145 million a year". Furthermore, WMO has estimated "that overall economic benefits of modern meteorological services typically outweigh the national cost of maintaining such services by a ratio of as much as 10 to 1".

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[4] The Sixth World Meteorological Organisation Long Term Plan (2004-2011).

For Europe this would lead to the following figures: The total annual budget of European National Meteorological services and related organizations (EUMETSAT and European Centre for Medium-Range Weather Forecasts is roughly between 1.8 and 2 billion Euros. On the basis of the WMO calculation, the economic benefits can be estimated between 18 and 20 billion Euros per year.

The European Union Radio Spectrum Policy Group (RSPG), in its Report and Opinion on "a Coordinated EU Spectrum Approach for Scientific Use of Radio Spectrum" (25 October 2006) concludes in particular that :

– "Scientific use of spectrum has a considerable societal value. Most of the data retrieved from the use of the so-called "scientific bands" are directly dedicated to the benefit of every citizen as they relate in particular to meteorology, climatology, environment, civil security and fundamental research. Most of the associated investments are coming from public funds."

– "Most of this societal value is incommensurable in financial terms, as they relate to preventing large losses of lives or threats to socio-political stability and security. However, scientific use of spectrum also has a direct impact in many economic areas, which can be estimated, and in producing economic spin-offs in technology and economic developments in energy, transportation, agriculture, communications, medicine, etc."

The long-term economic impact of information from remote sensing satellites is substantial, in both the production of food and other agriculture products and the operation of businesses and industries that are dependent on both local weather and long-term climate stability. Civil aviation, shipping, land transportation take direct benefits and savings resulting from the timely preparation for adverse weather conditions.

Information from sensing systems is also used increasingly to provide scientifically based guidelines for environmental policy. For certain measurements, for example EESS sensing, the current data are compared with historical data. For these long-term measurements and trends long-term consistency of measurements is essential.

A.5 Status of radio spectrum used by Earth observation systems

A.5.1 Frequency bands used in GEOSS and specific protection requirements

The Global Earth Observation System of Systems (GEOSS) will provide comprehensive and coordinated Earth observations from thousands of instruments worldwide that will, on the one hand, come from existing national, regional, and international systems and, on the other hand, from new systems that will be specified to complete and ensure the global coverage of the Earth system.

The GEOSS will to a large extent rely on radio frequencies related to:

– satellite passive remote sensing, using all frequency bands allocated to EESS (passive);

– satellite active remote sensing, using all frequency bands allocated to EESS (active), for multiple purposes (Synthetic Aperture Radars (SAR), precipitation radars, cloud profile radars, altimeters, scatterometers …);

– satellite telecommand/control and data downloading from Earth exploration and meteorological satellites;

– ground-based observations, such as meteorological radars, wind profilers, radiosondes as well as ground-based passive sensors;

– forecasts and alerts broadcasting, making use of commercial satellite payloads in the 3.4-4.2 GHz and 10.7-11.7 GHz, these latter being of prime importance in large areas of the globe for propagation reasons.

Hence, a very important issue is the protection of the specific radio frequency bands to maintain the availability of these frequency bands and the reliability of GEOSS. Once more it is stressed that passive remote sensing depends on very specific frequencies because these measurements are based on the reception of natural electromagnetic emissions related to physical processes. These measurements cannot be performed at other frequencies.

The issue of protection of passive remote sensors, and in particular those using frequency bands covered by RR No. 5.340 (stating that "All emissions are prohibited …"), is a critical point by GEO. It has to be ensured that these radio frequencies are adequately protected and used solely by earth observation applications. These bands and the related sensors are by nature highly sensitive to interference (either in-band or out-of-band) and hence need specific care, to ensure that measurements will not be contaminated by other radio sources or man-made emissions.

Finally, even though the bands used for active sensors or applications (either space-borne of ground-based) are in principle less sensitive to interference than passive bands, sharing scenarios with other active services have to be developed very carefully in order to avoid jeopardising the measurements by existing and future sensors.

A.5.2 Harmonisation through the ITU Radio Regulations

From the beginning, the allocation, harmonisation, and protection of spectrum used by the Earth observation systems is achieved at the global level through WRC decisions which are incorporated in the Radio Regulations (RR) of the ITU. These Regulations have the status of an International Treaty.

This harmonisation means that specific frequency bands are reserved for a certain use worldwide or regionally. The nature of the frequency usage determines whether and how much harmonisation is necessary. National allocation tables generally comply with ITU RR and decisions of World Radiocommunication Conferences (WRC's).

With regard to Earth observation and meteorological applications, there is currently a very high level of global harmonisation for active applications noting that the Earth observation and meteorological communities and agencies coordinate among themselves to make the most efficient use of the corresponding frequency band. For passive bands, due their specific physical nature, there is an obvious de facto harmonisation.

The availability of sufficient and well-protected spectrum for telemetry/telecommand as well as for satellite down-linking of the collected data is also of great importance.

Finally, it should also be noted that the fixed-satellite service systems, through commercial payloads in the 3 400-4 200 MHz band and the 10 700-11 700 MHz band, are used globally to disseminate weather, water and climate related information, including disaster warnings to meteorological agencies and user communities. It has to be stressed that a large part of the population, in particular in developing countries, is heavily dependent on the use of 3.4-4.2 GHz satellites in areas where propagation conditions (e.g. heavy rain in tropical and equatorial zones) make the use of any other telecommunication support impractical.

WMO hence stresses the fact that a lack of any of this system's radio components, whether associated with measurement, collection or dissemination, is able to put at risk the whole meteorological process. 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 research has been recognized in Resolution 4 (CG-XV) of the WMO, attached as Annex 2.

A.5.3 Compatibility conditions

Exclusive use of a frequency band by Earth observation services is only necessary in a few cases. In general these services achieve a significant degree of sharing with other services, and among themselves.

A.5.3.1 Sharing in space based passive sensor bands

A limited set of bands is purely passive and for these bands all emissions are prohibited according to RR No. 5.340. The remaining issue in these bands is the compatibility with unwanted emissions received from active services allocated in adjacent or nearby bands. Due to specific physical characteristics, no frequency band used by passive services can be substituted by other bands.

Interference that could impact a given "passive" frequency band could have an impact on the overall measurement of atmospheric components; this is in particular important for meteorology and climatology.

Resolutions 750, 751 and 752, adopted by WRC-07 as a result of its Agenda items 1.2, and 1.20 include the latest ITU decisions about compatibility between the EESS (passive) and relevant active services.

For the protection of the EESS (passive) in bands protected by RR No. 5.340:

– Resolution 750 (WRC-07) specifies mandatory protection levels[5] for the following frequency bands:
  – 23.6-24.0 GHz for the inter-satellite service;
  – 31.3-31.5 GHz for the fixed service (excluding high altitude platform stations);
  – 50.2-50.4 GHz for the fixed-satellite (Earth-to-space) service;
  – 52.6-54.25 GHz for the fixed service.
– Resolution 750 (WRC-07) specifies recommended protection levels[6] for the bands:
  – 1 400-1 427 MHz for the radiolocation, the fixed, the mobile (except aeronautical mobile in the band 1 427-1 429 MHz), and the space operation (Earth-to-space) services;
  – 31.3-31.5 GHz for the fixed-satellite (Earth-to-space) service.

For the protection of EESS (passive) in bands not protected by RR No. 5.340:

– Resolution 752 (WRC-07) specifies mandatory sharing criteria[7] for the band 36-37 GHz for both the EESS (passive) and the fixed and mobile services;

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[5] *Resolves* 1of Resolution 750 (WRC-07) states that unwanted emissions of stations brought into use in the bands and services listed in a given table shall not exceed the corresponding limits in that table, subject to the specified conditions.

[6] *Resolves* 2 of Resolution 750 (WRC-07) urges administrations to take all reasonable steps to ensure that unwanted emissions of active service stations in the bands and services listed in a given table do not exceed the recommended maximum levels contained in that table, noting that EESS (passive) sensors provide worldwide measurements that benefit all countries, even if these sensors are not operated by their country.

[7] Resolution 752 (WRC-07) uses the words: shall comply with the sharing criteria contained in ...

- Resolution 751 (WRC-07) recommends specific criteria[8] for sharing between the EESS (passive) and the fixed and mobile services in the frequency band:
  - 10.6-10.68 GHz.

A.5.3.2 Sharing in space based active sensors bands

Nearly all the space based active sensors bands are shared with radiolocation; in some cases the bands are shared also with radionavigation. Many years of coexistence without interference problems have confirmed the compatibility of these services in the bands allocated.

A potentially critical sharing situation might develop in the range 5 250-5 350 MHz, where the decisions by WRC-03 only discourage but do not prohibit outdoor usage of wireless LAN. This part of the band is used for synthetic aperture radar (SAR) imaging and supports the main GMES space element.

Also, the 1 215-1 300 MHz band is an area of historical coexistence, but its conflicts are increasingly rising as new radiolocation systems and radionavigation satellite systems are deployed and more sensitive remote sensing radars such as the soil moisture active/passive radar are developed.

A.5.3.3 Sharing in space based data transmission bands (Earth-to-space, space-to-Earth)

In general, there are no difficult sharing situations in most of the bands used for space based data transmission. For the Earth-to-space emissions, the fact of having ground stations in relatively remote and naturally shielded sites limits any possible interference to terrestrial services. On the other hand, in some cases, the high power required to reach the satellite receivers ensures that typically no interference is suffered by the space science satellites from terrestrial systems.

Also the possibility of interference by terrestrial systems to the receiving ground station (space-to Earth transmission) is strongly limited by the remote location of these stations. As for the satellite part, by respecting the RR Article 21 limits, the space-to-Earth transmissions do not interfere with terrestrial systems. It should be noted that some EESS (space-to-Earth) bands are so intensive used that intra service coordination is required to avoid interference.

A.5.3.4 Sharing in the meteorological aids and Earth observation services bands

According to the RR, 2 sets of frequency bands are exclusively allocated to the Earth observation and meteorological services on a primary basis:

- The band 401-403 MHz is allocated to EESS and meteorological applications

  (NOTE 1 – 401-402 MHz has an allocation to SOS (space-to-Earth)).
- The following bands are exclusively allocated for meteorological services on a primary basis:
  - 403-406 MHz,
  - 1 690-1 700 MHz.

    NOTE 1 – RR Nos. 5.381 and 5.382 allocate this band also to other services on a primary basis in several administrations.

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[8] *Resolves* 1 of Resolution 751 (WRC-07) urges administrations to take all reasonable steps to comply with given sharing criteria, when bringing into use stations in the Earth exploration-satellite service (passive), the fixed service and the mobile, except aeronautical mobile, service, noting that EESS (passive) sensors provide worldwide measurements that benefit all countries, even if these sensors are not operated by their country.

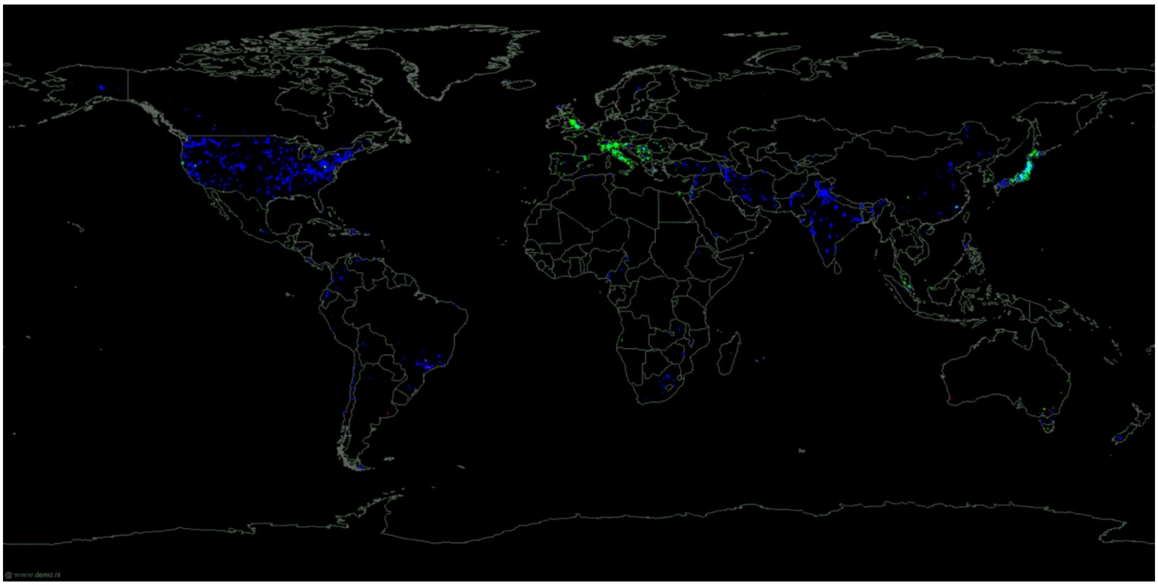
A.5.4 Impact of RFI on products

Radio frequency interference (RFI) can reduce the quality of meteorological and climatological products; therefore it is desirable to be able to determine if the input data have been corrupted. Detection of data errors then allows the resulting reduced reliability in forecasts and products to be noted and identified.

The impact of RFI on meteorological products is not well known because RFI is generally not anticipated unless there is *a priori* reason to suspect it may be present. Such an a priori reason would be active radiocommunication services co-allocated with passive services in the passive sensing frequency band or the use by a passive sensor of an unallocated frequency band that is used by active radiocommunication services. RFI, if present, might be treated erroneously as just another anomaly in the input data or model without specifically being suspected.

FIGURE A.15

Interference to AMSR-E passive sensor (blue is the 6-7 GHz and green the 10.6 GHz)



Degradation refers to a reduction in the quality of the environmental products. Degradation of product quality as well as communication errors can occur at two locations. The first location is in space where instrument measurement errors can be introduced by the measurement environment, improper calibration, or RFI. The second location (not to be discussed in this Report) is on the ground during ground operations. The degradation caused by RFI may be managed more effectively if it can be minimized and somewhat predicted. However, low level RFI can not be easily detected because it cannot be distinguished from natural radiation levels. This situation is potentially the most serious problem since degraded or incorrect measurements can be mistakenly accepted as valid measurements (see Figs A.15 and A16).

An additional example of interference to meteorological radar from a single indoor low power transmitter can be seen in Fig. A.17.

FIGURE A.16

Interference to SMOS passive sensor (strong interference at 1.4 GHz for ascending orbits)

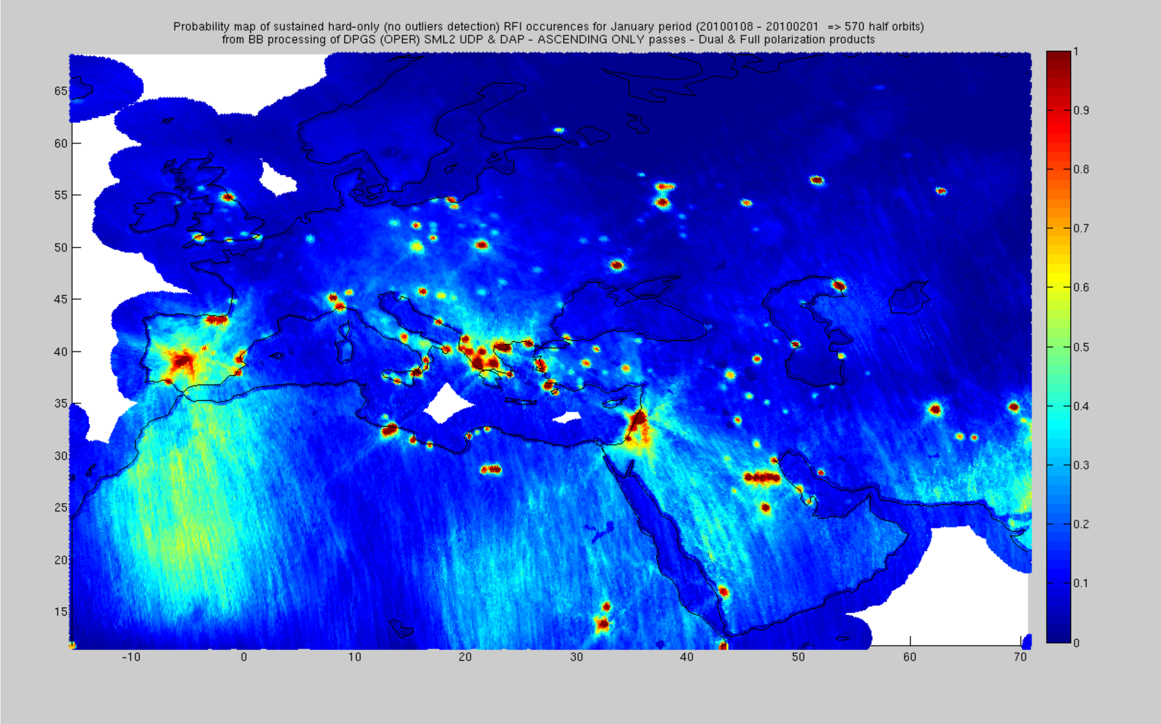
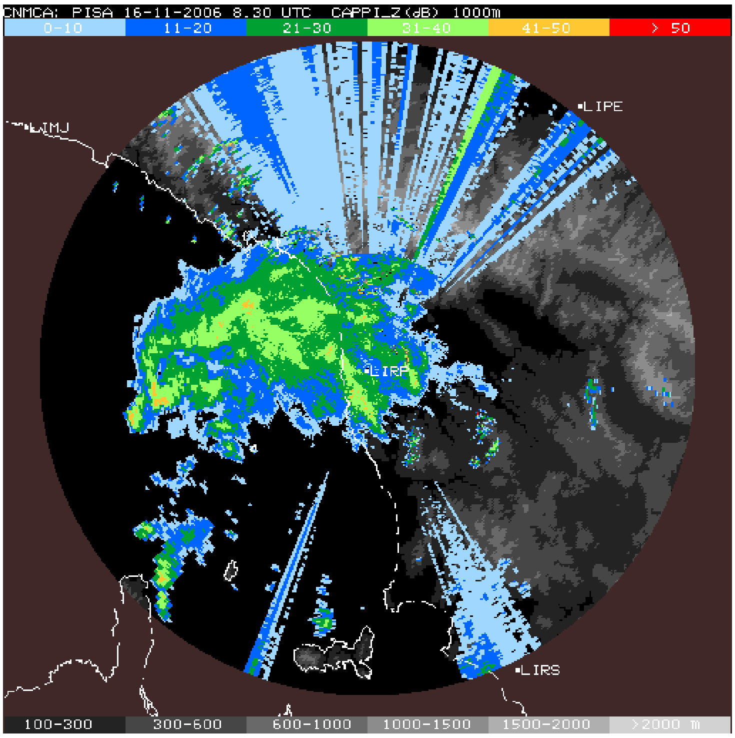


FIGURE A.17

Interference to meteorological radar (precipitation mode)



A.6 Conclusions

One can improve prediction of the Earth system only through comprehensive, systematic Earth observation. Observing what is happening today and analyzing what has happened in the past, are the keys to understanding and predicting what will happen in the future.

Earth observation applications represent worldwide essential activities. Sustained operation of terrestrial, oceanic, air-borne and space-based observation networks is critical for evidence-based policy decisions about the environment and enables better predictions of natural disasters, of epidemics, of the impact of energy choices, or of variations in the climate.

The considerable societal value of Earth observation can directly be translated into terms of societal weight and economic value of the radio-spectrum which is used for these Earth observation activities. Most of the data retrieved from the use of this spectrum are directly dedicated to the benefit of every citizen.

Most of this societal value is incommensurable in financial terms, as it relates to preventing large losses of lives or threats to socio-political stability and security. Scientific use of spectrum has also a direct impact in many economic areas, which can be estimated, by producing spin-offs in technology and economic developments in energy, transportation, agriculture, communications, etc. The benefits thereof relate to society as a whole, may be difficult to foresee and may be realised over very long periods of time.

The WMO has estimated that overall economic benefits of modern meteorological services typically outweigh the national cost of maintaining such services by a ratio of as much as 10 to 1.

The World Bank provided information that, during the 90's, an efficient warning system could have decreased the economic impact of natural disasters by 240 billion dollars and that it is reasonable to assume that the cost-effectiveness of anticipatory measures will apply at least as much to catastrophes of global extent as to local natural disasters.

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 $. 90% 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.

Nowadays, Earth observation activities are organised at a global level, in particular within the Group on Earth Observation (GEO) and, therefore, spectrum related issues must be considered globally since unilateral Decisions may have worldwide impact on related frequencies use and measurements.

In particular, due to the specificity and uniqueness of passive bands there are no alternatives to gather the same information. Therefore the passive bands are unsuitable for migration and any potential interference would lead to the loss of these unique, essential and increasingly important data.

To this respect, it should be recognised that Earth observations are totally relying on radio-frequencies, included in global systems that may be at risk if any of this system's radio components, whether associated with measurement, collection or dissemination, is lacking or under threat.

Recognizing that Earth observations are nowadays essential activities that are totally relying on radio-frequencies, the essential role and global importance of Earth observation radiocommunications applications need to be stressed and recognised and international protection and long-term availability of related frequency bands is therefore a goal to be reached and supported by all ITU Members.

Annex 1
to Part A

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Annex 2
to Part A: WMO Resolution

World Meteorological Organisation

RESOLUTION 4 (CG-XV)

Radio frequencies for meteorological and related environmental activities

The Congress,

Noting:

1. The WMO Strategic Plan and the United Nations Millennium Development Goals,
2. Resolution 3 (Cg-XIV) "Radio frequencies for meteorological and related environmental activities",
3. The current radio-frequency allocations and regulatory provisions related to the meteorological aids, meteorological satellite, Earth exploration satellite and radiolocation (weather and wind profiler radars) services in the Radio Regulations of the International Telecommunication Union (ITU),
4. The outcomes of the ITU World Radiocommunication Conferences (WRC), especially WRC-2000 and WRC-03,
5. The agenda of the forthcoming ITU World Radiocommunication Conference-2007 (WRC-07) and related WMO positions submitted during the ITU preparatory process,

Considering:

1. The prime importance of the specific radiocommunication services for meteorological and related environmental activities required for the prevention, detection, early warning and mitigation of natural and technological (human-made) disasters, the safety of life and property, the protection of the environment, climate change studies and scientific research,
2. The importance of information provided by the Earth exploration systems, including meteorological systems for a wide range of economic activities such as agriculture, transportation, construction and tourism,
3. The crucial importance of the allocation of suitable radio-frequency bands for the operation of surface-based meteorological observing systems, including in particular radiosondes, weather radars and wind profiler radars,
4. The crucial importance of the allocation of suitable radio-frequency bands for the operation of meteorological and research and development satellites, including remote sensing, data collection and data distribution links,

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

Expresses its serious concern at the continuing threat to several frequency bands allocated to the meteorological aids, meteorological satellite, Earth exploration-satellite and radiolocation (weather and wind profiler radars) services posed by the development of other radiocommunication,

Requests the Commission for basic systems to pursue the continuous review of regulatory and technical matters related to radio frequencies for operational and research meteorological and related environmental activities, and preparation of guidance and information for national meteorological and hydrological services, in coordination with other technical commissions, especially the Commission for Instruments and Methods of Observation, and in liaison with other relevant international bodies, in particular the Coordination Group for meteorological satellites;

Urges all Members to do their utmost to ensure the availability and protection of suitable radiofrequency bands required for meteorological and related environmental operations and research, and in particular:

1. To ensure that their national radiocommunication administrations are fully aware of the importance of and requirements for radio frequencies for meteorological and related activities, and to seek their support in the ITU World Radiocommunication Conferences and Radiocommunication Sector (ITU-R) activities;
2. To participate actively in the national, regional and international activities on relevant radiocommunication regulatory issues and, in particular, to involve experts from their services in the work of relevant regional radiocommunication organizations and of ITU-R, especially ITU-R Study Group 7 on science services;
3. To register adequately with their national radiocommunication administrations all radiocommunication stations and radio frequencies used for meteorological and related environmental operations and research;

Appeals to the International Telecommunication Union and its Member Administrations:

1. To ensure the availability and absolute protection of the radio-frequency bands which, due to their special physical characteristics, are a unique natural resource for space-borne passive sensing of the atmosphere and the Earth surface; in this regard, the exclusive 23.6-24 GHz passive band that is associated with a water vapour absorption line is of crucial importance for weather, water and climate research and operations;
2. To give due consideration to the WMO requirements for radio-frequency allocations and regulatory provisions for meteorological and related environmental operations and research;
3. To pay special attention to the WMO positions related to the WRC-07 agenda, in the light of **Appeals** (1) and (2) above;

Requests the Secretary-General:

1) To bring this Resolution to the attention of all concerned, including the International Telecommunication Union;
2) To pursue as a matter of high priority the coordination role of the Secretariat in radiofrequency matters, especially with ITU-R, including participation of WMO in ITU-R Study Groups, conference preparatory meetings and World Radiocommunication Conferences;
3) To facilitate the coordination between national meteorological and hydrological services and their national radiocommunication administrations, particularly in preparing the ITU World Radiocommunication Conferences, by providing appropriate information and documentation;
4) To assist the Commission for basic systems in the implementation of this Resolution.

Annex 3
to Part A: Cape Town Declaration

Cape Town Declaration of the Earth Observation Ministerial Summit

We, the participants assembled at the Group on Earth Observations Ministerial Summit in Cape Town, South Africa, on 30 November 2007:

Recognizing that nations are facing major environmental, social and economic challenges as a consequence of global change;

Recognizing that sound policymaking for addressing the environment and sustainable development must be based on understanding, describing and predicting a complex and interdependent world, and therefore requires terrestrial, oceanic, air-borne, and space-based Earth observations, data assimilation techniques and Earth system modelling;

Recalling that the 2002 World Summit on Sustainable Development (WSSD) stressed the importance of Earth observation systems for advancing sustainable development, particularly in developing countries;

Recalling that the G8 Summit in Evian in 2003 committed to strengthen international cooperation on global observation and associated information systems and the G8 Summits in Gleneagles in 2005 and Heiligendamm in 2007 affirmed the role of the Global Earth Observation System of Systems (GEOSS);

Recalling that the Group on Earth Observations was founded on the principle of using coordinated, comprehensive and sustained Earth observations to enhance human health, safety and welfare, alleviate human suffering including poverty, protect the global environment and achieve sustainable development;

Reaffirming the outcomes of the Earth Observation Summits in Washington in 2003, Tokyo in 2004 and Brussels in 2005 that established the Group on Earth Observations (GEO) and endorsed the 10-Year Implementation Plan for building GEOSS;

Recognizing that GEOSS will continue to build upon the interlinking and strengthening of existing and future observation, prediction and information systems developed and operated by Members and Participating Organizations, within the scope of the 10-Year Implementation Plan;

Recognizing the importance of providing stable, reliable and long-term operations of Earth observation networks and systems within the framework of national policies and international obligations;

Recognizing the important contribution GEOSS can make through collaboration with UN system bodies including in response to the needs of the United Nations Framework Convention on Climate Change (UNFCCC), the Convention on Biological Diversity (CBD), United Nations Convention on Combating Desertification (UNCCD), and other relevant agreements and processes, and the growing need to further enhance such contributions;

Recognizing that GEOSS can contribute to the development of the United Nations Spatial Data Infrastructure (UNSDI);

Recognizing the important contribution GEO can make through collaboration with the International Telecommunication Union to promote, by the appropriate alerting authorities, the implementation of the international standard for all-media public warning across all disaster and emergency situations;

Reaffirming that GEO is addressing user needs focussed on multiple societal benefit areas;

We note with satisfaction the numerous contributions and early achievements made by Members and Participating Organisations towards the GEOSS 10-Year Implementation Plan, as described in the *GEO Report on Progress 2007*. These contributions and early achievements are delivering multiple social, environmental and economic benefits such as facilitating access to observations, data and products, enhancing resilience to natural disasters, improving energy, water and resources management, improving monitoring and forecasting capabilities for climate, air quality and epidemics and facilitating the protection of ecosystems and the services they provide;

In evolving from concept to action and implementation, we envision GEO providing a significant international framework to increase the benefits of national and regional investments in global Earth observation, prediction and information systems;

We confirm our common view that:

a) the sustained operation of terrestrial, oceanic, air-borne, and space-based observations networks is critical for informed decision making;

b) data interoperability is critical for the improvement and expansion of observational, modelling, data assimilation and prediction capabilities;

c) continued research and development activities and coherent planning are essential for future observation systems;

d) continued cooperation and dialogue will establish GEOSS as a powerful means to support informed decision making;

e) coordination at national, regional and global levels, continued investments, scientific and technological advances and innovative approaches to financing will be vital for upgrading and expanding Earth observations and building the capacity of individuals, institutions and systems, particularly in developing countries.

We support the establishment of a process with the objective to reach a consensus on the implementation of the Data Sharing Principles for GEOSS to be presented to the next GEO Ministerial Summit. The success of GEOSS will depend on a commitment by all GEO partners to work together to ensure timely, global and open access to data and products;

We commit to explore ways and means for the sustained operations of the shared architectural GEOSS components and related information infrastructure.

We welcome the Resolution of the World Radio Conference-07 on radiocommunication use for Earth observation applications and the support it provides for the international protection and long term availability of frequencies for terrestrial, oceanic, air-borne, and space-based observations, including passive measurements;

We commit ourselves to working together to improve the interoperability of and access to observation and associated prediction and information systems towards the continued strengthening of GEOSS and the full realisation of the 10-Year Implementation Plan;

We thank the Government of the Republic of South Africa for organizing and hosting today's Summit and thus advancing international cooperation on Earth observation systems;

We resolve to meet again before the end of 2010 to review progress, conduct a mid-term assessment and give further guidance on the implementation of GEOSS.

PART B

Solar radio monitoring

B.1 Introduction

Many of the phenomena discussed in Part A are driven by the Sun. This is universally accepted. However, what is unfortunately not as widely appreciated is that the Sun is not a consistent or constant engine. Its changing behaviour has significant ramifications for activities and processes on Earth, some of which can have disastrous impacts on our infrastructure and technology, and can endanger human life.

The monitoring activities described here are radio-astronomical measurements of solar radio emissions.

B.1.1 The Sun

The Sun is a typical yellow dwarf star. It is basically a large ball of gas, some 1.4 million kilometres in diameter, consisting mainly of hydrogen and helium, and comprises 99.8% of the total mass of the solar system. The temperature at the centre is approximately 15 million Kelvin, which is hot enough for hydrogen nuclei to combine to form helium. This is the source of the Sun's energy. This energy finds its way to the "surface" (more correctly, the photosphere), where the temperature is approximately 6 000 Kelvin, and is radiated into space. The Sun's total energy output is equivalent to the total conversion into energy of 4 million tonnes of solar material per second.

However, this is not the whole story. When the Sun formed from a collapsing cloud of interstellar dust and gas, it also captured some of the interstellar magnetic field. This has been amplified by rotational shear and fluid flows in the Sun to generate varying magnetic fields that affect solar structure and act as energy reservoirs.

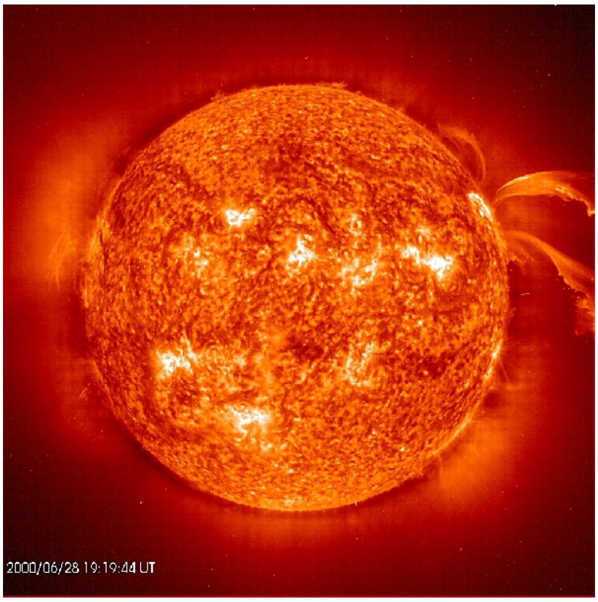
Figure B.1 shows an image of the Sun obtained using the Solar Heliospheric Observatory. The bright patches on the surface indicate concentrations of magnetic flux. The structures beyond the edge of the disc are solar plasma supported in magnetic fields.

The image also shows the solar corona, a thick layer of very hot (millions of Kelvin) gas overlying the photosphere. This layer is unstable, and is constantly blown off into space at speeds of hundreds to thousands of kilometres per second, forming what is now referred to as the solar wind. The hot gas in the corona remains predominantly bound to the Sun's magnetic field, as though enclosed inside a cage. However, some of this gas escapes, in events known as *coronal mass ejections,* streaming through interplanetary space with speeds of up to three million kilometres per hour, (see Fig. B.2).

The magnetic fields and associated trapped plasma are highly elastic and can store enormous amounts of energy. Eventually, instabilities lead to the explosive release of that energy. These events, known as solar flares, radiate X-rays and high-energy particles, and trigger coronal mass ejections.

FIGURE B.1

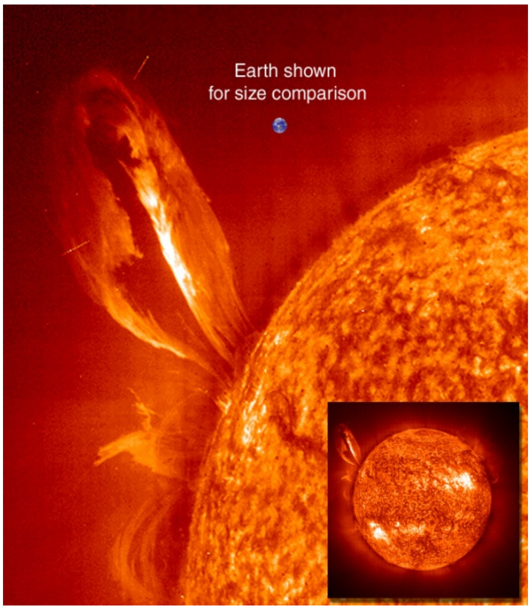
Solar Image



Source: Solar and Heliospheric Observatory (SOHO)[9]

FIGURE B.2

Large Protuberance[10]



Source SOHO

B.1.2 Space weather

Our growing appreciation of our susceptibility to the Sun's behavior has led to the development of a new discipline called "space weather" (cf. e.g. esa-spaceweather.net). Space weather, like its more familiar counterpart closer to the ground, is the study of the changing conditions in the region of space near the Earth. However, instead of studying wind and rain, space weather scientists measure electromagnetic radiation and the behaviour of solar plasma.

On long and intermediate timescales, the consequences of solar variability upon climate are ranked with the effects of terrestrial volcanism and the summation of all human activitiy. More important on shorter timescales is the role of space weather in disrupting our technical infrastructure in space, in the air and on the ground.

Solar radio monitoring is a specialized branch of radio astronomy. It plays an active role in space weather services and research, and facilitates – through the monitoring of solar activity – space weather forecasting and the generation of timely alerts of solar eruptive events that can impact the Earth and human activities.

On short timescales, data from ground-based radio spectrographs immediately show the presence of solar flares and coronal mass ejections, which, when combined with complementary data from satellites, provide estimates of their strength, ejection speed and direction of propagation. This information permits us to infer the severity of the disturbance and its probable time of arrival

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[9] SOHO, the Solar and Heliospheric Observatory is a project of international collaboration between ESA and NASA to study the Sun from its deep core to the outer corona and the solar wind.

[10] http://www.mps.mpg.de/images/forschung/sonne/sonne002.jpg. Large, eruptive prominence in He II emission at 304Å, with an image of the Earth added for size comparison. This prominence from 24 July 1999 is particularly large and looping, extending over 35 Earth radii out from the Sun. Erupting prominences can affect communications, navigation systems, even power grids, while also producing auroras visible in the night skies.

at Earth, making it possible to mitigate the adverse effects on a wide variety of human technologies, such as telecommunications, satellite-based navigation systems, space activities (satellites, manned missions), aviation and electrical power grids.

Several solar radio observatories are distributed over the Earth to provide continuous round-the-clock monitoring. Information about the multiple solar radio telescopes in Europe can be found on the CESRA[11] web site (http://www.lesia.obspm.fr/cesra/). A similar network is also operated by the US Air Force.

Our sensitivity to space weather is now widely appreciated, and this is being reflected at national and international policy levels. Several new initiatives, such as the "European Space Situational Awareness Initiative" (cf. e.g. www.cdi.org/pdfs/delmonte.pdf) have been started, in which a key segment is the impact of solar disturbances.

A longer term consideration, but still a major natural hazard to be considered, is the possibility of giant solar flares, such as the one that occurred in 1859. These seem to occur randomly. None have occurred since the appearance of our modern, technologically dependent society, with its extreme reliance on power and communication infrastructure. The impact of one of these events would be severe and could have major worldwide disrupting consequences that should be better assessed, as such an extreme situation is unprecedented[12].

This major new global technological risk cannot be controlled, which highlights the crucial role played by early-warning systems that rely on continuous monitoring of the Sun to mitigate its effects. Ground-based solar radio telescopes are one of such early-warning systems.

Flares and other transient events are only the most dramatic aspect of solar activity that affect us. Solar radio emissions are also indicators of other space weather phenomena that can have very serious effects on systems and activities in space, in the atmosphere and on the ground.

The importance of space weather has led to ground-based monitoring by solar radio telescopes and other flux monitors, which are complemented by spaceborne monitoring of solar particles and emissions at wavelengths that do not reach the ground. As an example, the Royal Observatory of Belgium has instruments for research into plasma physics and space weather on board the PROBA2 satellite.

Space weather forecasting and the centralization of the storage of relevant data are now important activities carried out at a number of centres around the world. Examples include the data and forecast centre operated by the US National Oceanic and Atmospheric Administration, the Canadian Space weather forecasting Centre and the Solar Influences Data Analysis Centre (SIDAC), a department of the Royal Observatory of Belgium. An example of the daily space weather forecasts produced by SIDAC is shown in Fig. B.3.

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[11] CESRA : Community of European Solar Radio Astronomers.

[12] A recent article: www.newscientist.com/article/mg20127001.300-space-storm-alert-90-seconds-from-catastrophe.html.

FIGURE B.3

SIDAC – RWC BELGIUM Wed Dec 16 2009, 12.40 UT

Solar activity is expected to reach active levels, with risks of C-class flaring activity from NOAA AR 1035. A C5 flare occurred in this AR at 01:35UT on Dec. 16th. This Region still has potential for producing new C-class flares.
Geomagnetic activity is expected to be mostly quiet for the next 48 hours.

B.1.3 Objectives of solar monitoring

The objectives of solar radio monitoring are:

– to better understand solar-driven changes in the climate and other environmental parameters that have scientific, economic or humanitarian impacts;

– to understand and forecast space weather phenomena that affect our communications, transportation or other infrastructure, and activities such as agriculture and fisheries.

The phenomena and issues discussed in Part A cannot be considered as being confined to the Earth. They are driven directly or indirectly by the Sun. It is common in addressing many environmental and terrestrial issues to assume that the Sun is simply a constant energy source. In fact the Sun produces a complex and ever changing mixture of particles and electromagnetic waves, modulated by the general level of solar magnetic activity. Consequences can be felt in space, throughout the Earth's atmosphere, in the oceans and on the surface of the Earth. Solar activity plays an important role in the environmental and other issues discussed in Part A.

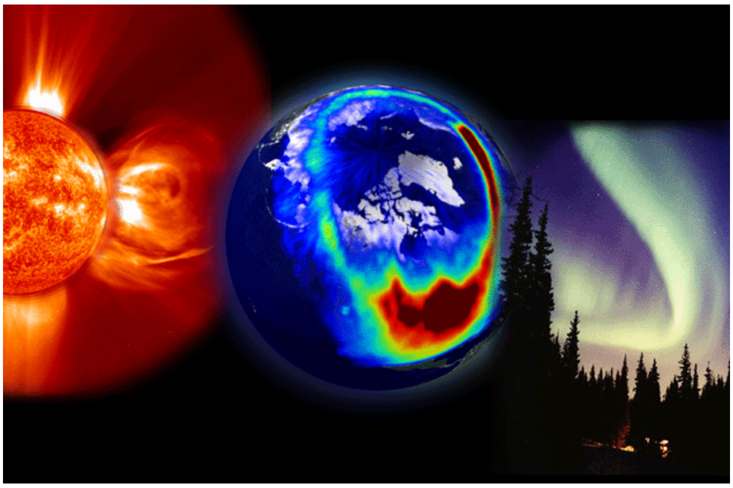
Solar activity is primarily a magnetic phenomenon. There are many ways of monitoring it, such as monitoring sunspot number and by satellites dedicated to observing the Sun, (see Fig. B.4).

Radio measurements have the advantage that they can be made automatically from the ground. They require little or no human interpretation, and are relatively inexpensive to make. It is possible to maintain data calibration, quality and consistency over long periods, which yields another important advantage in that this makes it easier to update and replace other instruments, and to set up international programmes of compatible monitoring activity.

Measurement of solar radio emission will remain an important part of the monitoring of the driving force disturbing our environment. This emission has no discernable direct effect on our environment or technologies, apart from the rare occasions when the solar radio emission is strong enough to degrade radio systems, which has happened on several occasions. Radio observations provide excellent stethoscopes on facets of solar behaviour that can have dramatic effects on our environment and activities on Earth, in the atmosphere and in space. The impact of solar activity on our environment, activities and infrastructure is manifold. A particularly dramatic example occurred in March, 1989 during a period of high activity that included a very large flare, which produced a terrestrial impact costing more than a billion US $. Figure B.5 shows a picture of a transformer destroyed in March 1989 by currents induced by the geomagnetic storm caused by that solar activity. The impact of a solar flare a few times that size, but similar to the one that occurred in 1859, would be much larger. Estimates by NOAA and others place the costs between 2 and 3 trillion US $, and recovery from it would take between 2 and 3 years (because of the requirement to replace items that cost millions of dollars and large numbers of which are deemed to be too expensive to be kept as spares). In addition, the continually changing level of solar activity causes a gradual degradation of power transformers, corrosion of long-distance pipelines, and many other adverse effects.

FIGURE B.4

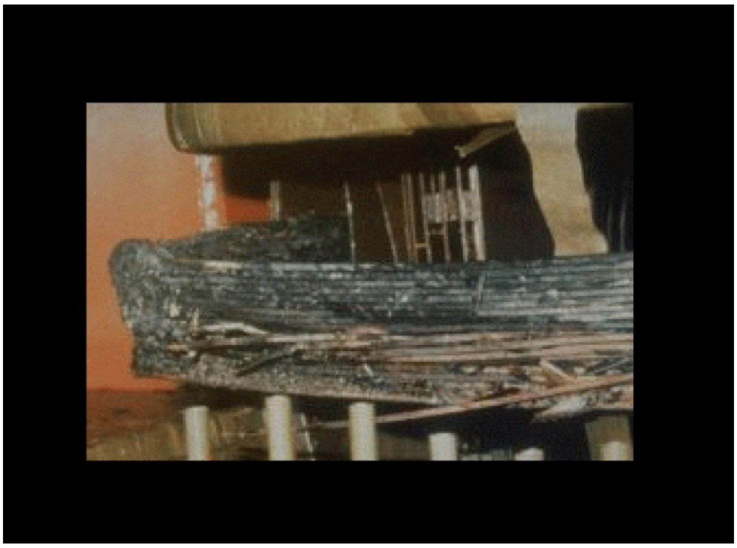
Solar activity seen from a satellite and from the ground



Source: SOHO

FIGURE B.5

Burned out transformer from an electrical power distribution network caused by solar activity on 13 March, 1989



B.2 Overview of solar radio monitoring

There are two main facets to solar radio monitoring. Firstly radio measurements are direct indicators of the level and nature of solar activity. Secondly there is the use of radio data as proxies for other solar or terrestrial quantities that are difficult or impossible to measure with the required accuracy or continuity. Examples of the latter are the use of solar radio fluxes to estimate ultra-violet fluxes and the consequent degree of heating of the upper atmosphere, which affects the management of satellite orbits.

The instruments, termed solar radio flux monitors, are essentially specially-designed radio telescopes. Their antennas are small, in order to "see" all of the solar disc with equal sensitivity, and their receivers have very high, linear dynamic ranges compared with those used for general radio astronomy. Figure B.6 shows two typical examples of such instruments. It depicts a pair of identical solar flux monitors near Penticton (Canada) being operated in parallel by the National Research Council's (NRC) Dominion Radio Astrophysical Observatory. These measure the 2.8 GHz (10.7 cm) solar radio flux, which is an internationally-used index of solar activity.

FIGURE B.6

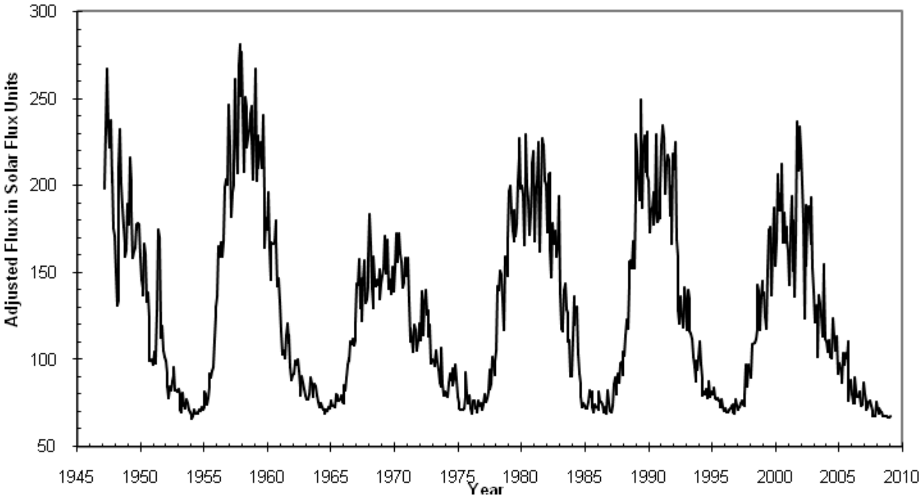
Two solar radio flux monitors operated near Penticton by the NRC

Monthly-averaged values of the 2.8 GHz solar radio flux since the beginning of the programme in 1947 are shown in Fig. B.7.

Occasionally measurements are degraded by the occurrence of flares. To provide the dynamic range required to record large flares while at the same time measuring the flux with sufficient precision, two data streams are generated, one 100 times less sensitive than the other. Figure B.8 shows a flux measurement being strongly degraded by a flare that occurred during the flux determination.

FIGURE B.7

Annually-averaged values of the 2.8 GHz solar radio flux as observed by the NRC since 1947



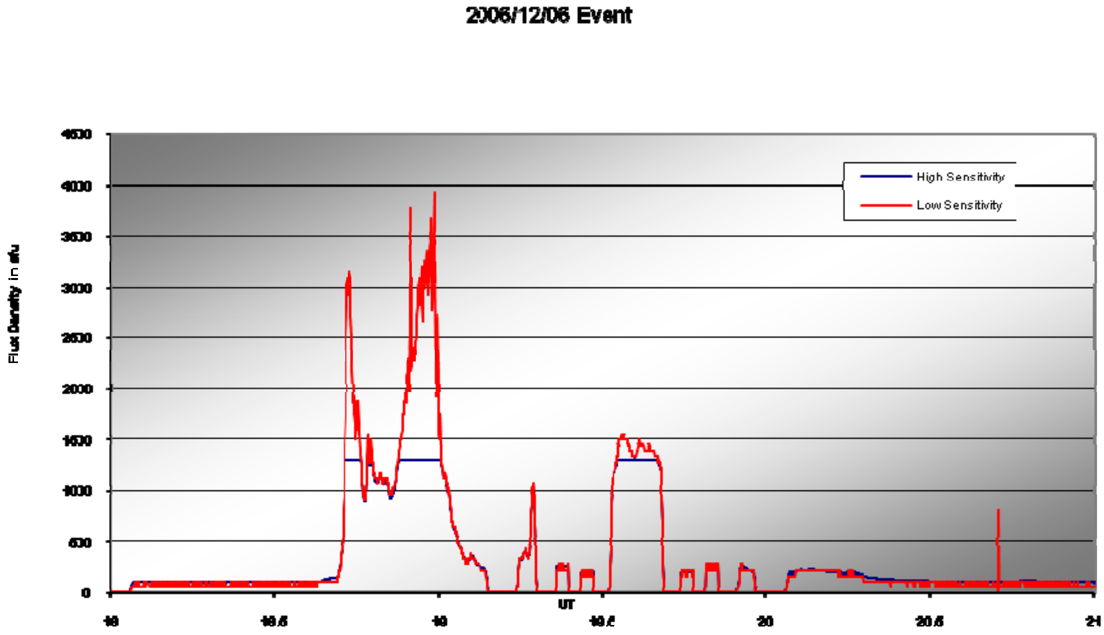
Many studies have shown that the measured radio flux is highly correlated with recent space measurements in the UV and X-rays, and with solar wind parameters, which are the main drivers influencing the dynamics and energy balance of the Earth’s atmosphere. As those wavelengths play a direct role in heating the upper layers of the Earth’s atmosphere (thermosphere), the 2.8 GHz solar radio flux index is currently used for the prediction of atmospheric drag on satellites and the maintenance of their orbits (e.g. through the ESA SPENVIS[13] service: www.spenvis.oma.be). However, measurements from space have only been available during the last 10 to 20 years. They cannot provide long-term continuity in the future, given the limited lifetime of space satellites.

The 2.8 GHz solar radio flux is extensively used to build long-term proxies. This enables semi-empirical scaling relations representing the solar spectral irradiance to be extrapolated backwards in time to important spectral domains, long before it could be measured. It is now possible to go even further back in time by correlating with the so-called cosmogenic isotopes in ice cores extracted from polar ice caps. The isotope abundances give only relative variations and must be calibrated from direct solar measurements over extended periods of time. Together with the visual sunspot index, the 2.8 GHz solar radio flux is almost the only direct absolute index available, and thus it plays a key role in this ongoing investigation.

The 2.8 GHz frequency was chosen for historical reasons, but is still only a sample at one frequency from an emission continuum extending from 0.5 to 10 GHz (called the “S-component”), which is produced by different structures on the Sun. In order to better understand the sources of this emission and to improve the long-term “climate” proxies, it is necessary to measure the flux at multiple wavelengths across this S-spectrum. In order to achieve this, new solar flux monitors are planned for Europe, North-America and Japan. Absolute measurements can only be carried out in the few protected radio astronomy bands available in this frequency range so it is essential to keep these bands clean to preserve a window to the Sun.

FIGURE B.8

A large solar flare that occurred during a flux determination. The black plot is the high-sensitivity channel, which overloaded; the red plot is the low-sensitivity channel, which is designed to accommodate the strong emissions from flares



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[13] SPENVIS: Space Environment Information System.

B.3 Solar radio flux data applications

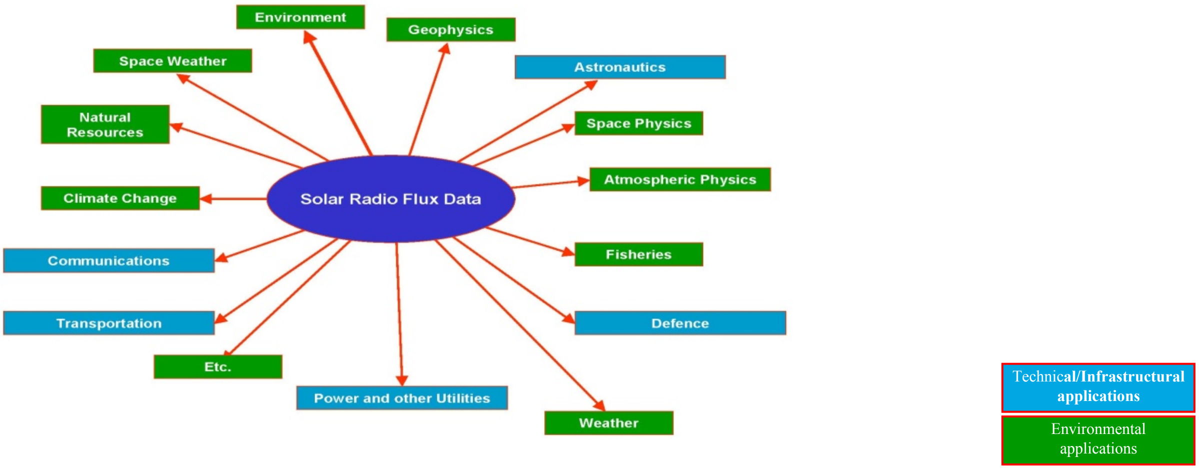
The applications to which solar radio flux data can contribute useful information fall into two broad categories: environmental and technical/infrastructural. These are summarized in Fig. B.9.

B.3.1 Environmental applications

Solar radio emission can act as a proxy for all solar radiation of environmental importance. For example, solar radiation at a variety of wavelength ranges provides energy input to several levels of the atmosphere. This affects the vertical temperature structure of both the ionosphere (the degree of ionization) and the atmosphere above a height of ~80 km. These are parameters measured by a variety of environmental sensors, but to have context or feasibility for modelling, the drivers need to be quantified, and these drivers are solar-driven. For example, the density of the upper atmosphere (above a hundred kilometres) is modelled using the 2.8 GHz solar radio flux as an (empirical) input.

FIGURE B.9

Service-centred chart of applications of solar radio flux data



B.3.2 Technical/Infrastructural applications

There are occasions when solar noise emissions, particularly in the VHF part of the spectrum, are strong enough to degrade communications and other radio systems by increasing their noise levels. These applications are partially summarized in Fig. B.10.

B.3.2.1 Solar-driven effects on satellites

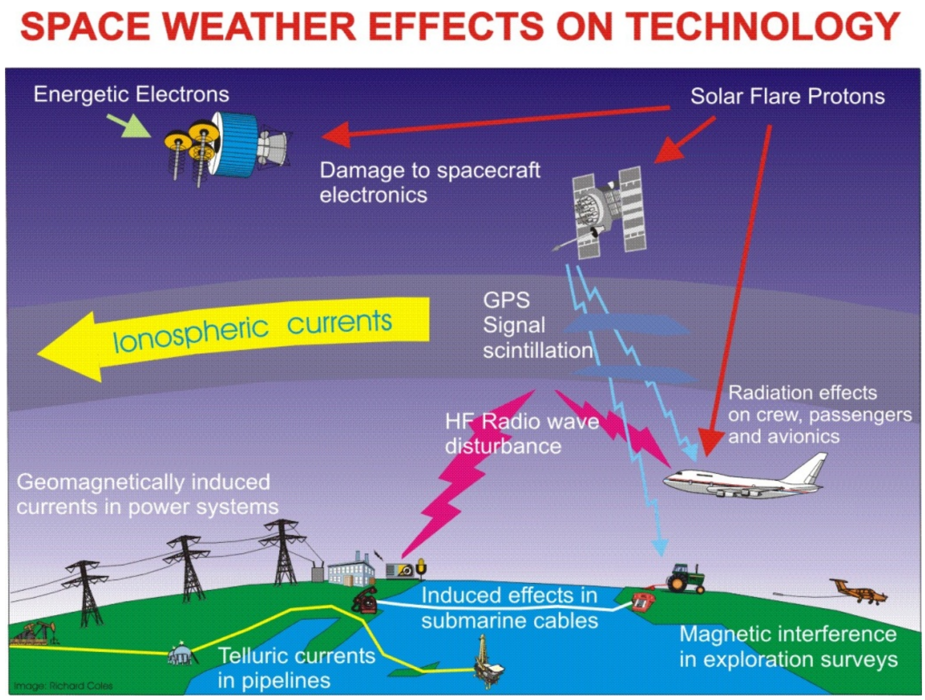
Satellites operate in an environment populated by high-energy particles, most of which come from the Sun or are accelerated locally through processes driven by the Sun. These can cause either temporary degradation or permanent damage to satellite electronics. In addition, they cause an accumulation of charge on the spacecraft (spacecraft charging), which can degrade or destroy equipment, or create phantom commands, which disrupt spacecraft operation.

Satellites in low Earth orbit (LEO’s) also experience the effects of increased atmospheric drag, which causes errors in their positions and enhanced rates of orbital decay. This increase is a result of solar activity causing a heating and expansion of the upper atmosphere. In addition, enhanced geomagnetic activity driven by the Sun generates ionospheric currents, which produce additional heating. In this regard the Sun has the potential to directly interfere with or degrade the operation of the sensors discussed in Part A of this Report.

The general level of solar activity as indicated by radio indices such as the 2.8 GHz solar radio flux can be used to predict the degree of heating and expansion in the upper atmosphere and the consequences for satellite orbits. Organisations like the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) use the 2.8 GHz solar radio flux for this purpose.

FIGURE B.10

Picture summarizing the impact of solar-driven space weather effects on technology



B.3.2.2 Ionospheric effects

The Sun is responsible for the existence of the ionosphere. Changes in solar activity, and the concomitant changes in the distribution of ionization in the ionosphere, can result in enhanced communication or, if solar X-rays significantly increase the degree of ionization in the D-Region, a total blackout that may persist for hours. Even in these days of satellite communications, the ionosphere remains a very important aid to communications all over the world, and forecasting ionospheric conditions is still vital. The ITU is an important user of radio data as a diagnostic of ionospheric behaviour and for predictive purposes.

An increasing number of commercial aircraft use long-distance routes over the polar regions. These aircraft must be able to communicate with air traffic control centres at all times. At low and mid-latitudes, this is done mainly using VHF, supported by a dense, ground-based infrastructure. However, at high latitudes (>82º, where the geosynchronous satellite belt is permanently below the horizon) this infrastructure does not exist, and HF is used. Unfortunately, ionospheric disturbances are particularly common at high latitudes. These can cause severe disruption of vital communications, which leave aircraft without any means of communication.

Radio measurements of solar activity are used to explain the day-to-day behaviour of the ionosphere and to forecast ionospheric, and in particular polar ionospheric conditions, in order to provide sufficient notice for airlines and other users to make appropriate plans (see § B.3.1).

B.3.2.3 Geomagnetic effects on ground systems

The changing velocity and density of the solar wind, and especially the impact of plasmoid ejected during solar flares and other transient events, cause slow and rapid fluctuations in the Earth's magnetic field. These induce electrical currents in any long metal structures, such as power lines, pipelines, phone cables and railway tracks. In power lines the induced currents offset the operating points of transformers, which, if heavily loaded, can lead to saturation of the transformer core and overheating of the windings. At a low level of activity, this results in enhanced degradation and early failure. Major magnetic storms, such as the one on 13 March 1989 caused by the large solar flare on 10 March 1989, produce much larger currents, which can lead to immediate transformer failure (see Figure B.5). The arrival of the plasmoid (coronal mass ejection) triggered by this flare produced the geomagnetic storm that brought about the collapse of the power distribution network in Quebec, Canada. Quebec was without power for more than nine hours. The economic impact because of infrastructure failure and loss of industrial production was in the region of billions of dollars. The consequences of this period of solar activity were not limited to Quebec; they were world-wide.

Induced currents driven by solar activity can also affect other systems. For example, induced currents in railway tracks can interfere with signalling systems and train position sensing.

Magnetic disturbances can have serious effects on various activities relating to natural resources. Prospecting using magnetometers to detect buried ore bodies or other geological structures are degraded or completely disrupted. Directional drilling uses sensing of the Earth's magnetic field to determine the orientation of the drill bit. Geomagnetic activity causes uncertainties in these determinations so that work has to stop until more stable magnetic conditions return.

Another very important issue is that of pipeline corrosion. Induced currents caused by geomagnetic activity can result in small potential differences appearing across inhomogeneities in a pipe's metal, and also across welds, thus increasing the rate of cathodic corrosion. Since pipelines may span thousands of kilometres, often in a hostile terrain and climate, inspection and maintenance are expensive, but a failure may be even more expensive and the environmental consequences severe. Therefore inspection and maintenance models which take into account geomagnetic activity are needed.

In this context, solar radio monitoring has a dual role:

- It provides a patrol for flares and other transient events that could trigger the ejection of a plasmoid (a coronal mass ejection), which could result in a major geomagnetic storm at the Earth. In the 24-48 h delay between the ejection and the arrival of the plasmoid at the Earth, measures can be taken to avoid or minimize its effects. For example, by disabling the automatic transfer of load from failed electrical circuits to others, and by a reduction of voltage to provide more headroom in the transformers, power distribution networks in Canada avoided the catastrophic failures of March 1989, when another large flare occurred a few months later.
- It provides information on the day-to-day solar activity levels which can be used to determine the expected lower levels of geomagnetic activity, which can still disrupt some activities.

B.3.2.4 Air transportation systems

The commercial air transportation system is based upon providing safe, cost-effective and to the best possible extent, fast travel over long distances. In order to achieve this, long-haul trips are increasingly routed through high magnetic latitudes on great circle routes. It is at just these latitudes where high-energy particles accelerated by solar activity are precipitated into the atmosphere. These present a significant radiation hazard to flight safety. When such particle precipitation events are likely, it is current practice to change aircraft routings and use lower altitudes. However, in highly congested air space, routing changes must be coordinated through the air traffic control infrastructure, and above a latitude of ~82°, the geosynchronous radio relay satellites are all below an aircraft's horizon. There are no accessible VHF communication stations within range, and aircraft have to use HF communications. These are susceptible to degradation or complete blackout by solar activity, especially at high magnetic latitudes. Unless there are on-board radiation sensors, aircraft are unlikely to receive a warning of such a black out (see § B.3.2.2). If the solar activity has blacked out the HF communications, it becomes very dangerous to make unscheduled routing changes.

B.4 Impact and societal value

The societal importance of solar radio monitoring is extremely high. This falls into two broad categories:

- the provision of timely warning of solar events (e.g. flares and coronal mass ejections) that could significantly affect our infrastructure or our activities; and
- the measurement of solar magnetic activity that indicates lower but still significant levels of environmental and technological disturbance, where particular activities might be degraded or the accumulated effects of the activity could give rise to serious degradation of infrastructural elements (e.g. power line transformers; oil and gas pipelines).

An example of the first category occurred in March 1989 when errors at a major Canadian power utility resulted in ignorance of a warning of a major solar flare, which had been detected by solar radio monitors (see Fig. B.5). The impact of the major power outage that ensued when the coronal mass ejection caused significant damage totalled about 10 billion US $. A short time later, the warnings issued when there was another major flare were acted upon and there was no significant impact. The actions taken included reducing voltages to provide more headroom, and a disabling of the automatic transfer of loads from failing circuits to those still operating.

An example of the second category is the aggregate amount of cathodic corrosion produced in oil and gas pipelines due to currents induced by solar-driven fluctuations in the Earth's magnetic field, which needs to be incorporated into the inspection and maintenance programmes for the pipelines.

The radiation hazards and communication problems that solar activity produces for aircraft on high-latitude, long-haul polar routes are still being addressed. Solutions are needed, but at the moment none have been identified. However, no matter which solutions are finally implemented, the foundation will be provided by programmes of solar activity monitoring triggering rapid notice of significant solar events.

Since 1989, the world has become far more dependent upon world-wide communication networks and power distribution networks. This has made us more vulnerable than we were in 1989. Moreover, the 1989 event was not an example of the largest recorded flare, which actually occurred in 1859. Using the 1989 event as a reference, NOAA has estimated that a repetition of the 1859 event today would produce damage in the range 2-3 trillion US $. Much of that damage should be avoidable with appropriate monitoring of the Sun's behaviour.

B.5 Status of radio spectrum use for solar radio monitoring

B.5.1 Spectrum usage for solar radio monitoring

Some solar radio monitoring is carried out in frequency bands allocated to passive services, such as the radio astronomy service. However, some measurements are made outside these bands. For example, the 2.8 GHz solar radio flux is measured in the band 2 750-2 850 MHz because the first measurements were made using modified radar equipment. It was subsequently realised that this band is almost optimal for monitoring solar magnetic activity. It has therefore been used continuously for more than 60 years; changing the frequency, even if only slightly, would change the statistical character of this important data set.

B.5.2 Harmonisation through the ITU Radio Regulations

The use of bands not allocated to passive services, such as the band 2 750-2 850 MHz for measuring the 2.8 GHz solar radio flux, is opportunistic and protected by local measures, and therefore requires no additional protection measures by the ITU. In Canada and in the neighbouring part of the United States of America, this band is protected for solar radio monitoring activity through joint agreements.

However, since the 2.8 GHz solar radio flux is a heavily used index of solar activity, and since there could be other such solar radio quantities, administrations may consider it appropriate to list these uses as footnotes in the RR. Such footnotes should have an informative character.

B.5.3 Compatibility conditions

Solar radio monitoring uses a subset of radio-astronomical, observing techniques and is thus subject to the same interference and compatibility concerns. Existing Recommendations can be used as appropriate.

B.5.4 Impact of RFI on data

As solar flux density values (spectral power flux-densities) are significantly higher than those observed in most radio astronomical measurements, much smaller antennas are used, so the sensitivity to unwanted emissions through the far side lobes of the antenna is substantially the same as for other radio astronomical measurements. Unwanted emissions mainly impact the data in two ways. They may degrade the accuracy of solar flux measurements or they may produce output records that resemble the radio signatures of flares. The latter may result in the transmission of spurious solar event warnings, which have potentially high economic and societal impacts. It is crucial to do everything possible to ensure that warnings are genuine.

B.6 Conclusions

The Sun has the capability to directly degrade or damage infrastructure and technologies. In space it can damage or destroy satellite electronics and present hazards to astronauts. Heating and expansion of the upper atmosphere by solar activity perturbs the orbits of satellites in low Earth orbit. Closer to the ground, the ionosphere, which is sustained by the Sun, can be modified by solar activity to cause partial or total blockage of HF communications. Particle precipitation at high magnetic latitudes is a radiation hazard for aircraft on long-haul polar routes. In addition, disturbances to the polar ionosphere can degrade or obliterate HF communication, which is the only option for aircraft on those routes. Magnetic fluctuations arising from solar activity result in additional corrosion in pipelines and shorten the life of transformers in power networks. Magnetic storms can cause power outages and a degradation of infrastructure. The potential world-wide impact of a major flare has been estimated to be in the range 2-3 trillion US $.

There is now an increasing number of spacecraft dedicated to solar monitoring, which presents a wealth of information never before available. However, this does not detract from the value of ground-based monitoring programmes. The observations from space-based platforms cover relatively short timescales, so they depend upon the longer record of ground-based observations to give them context. In addition, spacecraft are vulnerable to degradation or even fatal damage from solar radiation. Deploying replacements takes time. Ground-based monitoring programmes are not vulnerable to solar activity and, in the remote case of problems, such as solar-induced power outages, the availability of on-site support makes repairs possible at short notice.

Monitoring of solar radio emission using ground-based instruments (small radio telescopes) provides a reliable, consistent and relatively inexpensive means of monitoring solar activity and providing warnings of transient events. After 60 years of this, it is a mature and well-understood programme.

Compared with 1989, we live in a more connected world and are therefore far more vulnerable to disruption by solar activity. Monitoring the Sun’s behaviour using robust, ground-based systems is more important now than it has ever been.

PART C

Radio astronomy and space research services

Summary

In Part C a description is given of some of the benefits resulting from the frontline, innovative technologies developed by the radio astronomy (RAS) and space research services (SRS). Many of these technologies are used by the applications described in Parts A and B, and have also found application in many other areas of telecommunication.

It remains difficult to quantify the essential role and global importance of the use of the spectrum for radio astronomy and space research because the benefits of such use relate to society as a whole. These may be difficult to foresee, especially as they may only be realized over very long periods of time. In many areas radio astronomy serves as a trailblazer in order to develop technologies, which later have spinoffs for the benefit of society. Much of the economic impact of radio astronomy is indirect.

C.1 Introduction to astronomy

Astronomy is concerned with the formation, evolution, dynamics and other characteristics of objects beyond the Earth's atmosphere, e.g. planets, comets, stars, galaxies, diffuse matter in space and the Universe itself.

This research seeks to answer some of the biggest questions that can be asked, such as how did the Universe begin (or did it begin), how big is it, how old is it, and how will it end (or will it end)? As the science that provides the framework knowledge of where we, and the planet on which we live, fit into the environment of the Universe, astronomy is a vital part of the culture of all mankind.

From the dawn of civilization, astronomy has provided important stepping-stones for human progress. Our calendar and system of timekeeping came from astronomy. Much of today's mathematics, such as trigonometry, logarithms and calculus[14] is the result of astronomical research.

Observations of the Universe are made at frequencies across the whole of the electromagnetic spectrum, and not just in the traditional visual or "optical" region. Each spectral range reveals different physical properties of the objects that astronomers study, and each requires different types of telescopes and detectors to receive and analyze the incoming radiation. Radio astronomers study celestial objects and how they radiate energy in the radio spectrum.

The start of radio astronomy observations, nearly 80 years ago, led to the rapid development of advanced technology with regard to the design and building of very sensitive receivers and antennas with very high gain. Astronomy's appetite for computational power drove the development of many of the earliest electronic computers. The space age, which brought the communication and weather satellites upon which we depend each day, would not have been possible without the fundamental knowledge of gravity and orbits discovered by astronomers. Even the satellite communications industry as a whole was made possible as a result of the development of low-noise radio receivers for astronomers. Indeed, the image-processing techniques developed by astronomers are now part of the medical imaging systems that allow non-invasive examination of patient's internal organs. At today's observatories, the need of astronomers for better instruments continues to drive

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[14] Calculus is the mathematics used in the study of change, in the same way that geometry is the study of shape and algebra is the study of operations and their application to solving equations.

developments in such diverse fields as electronics, mechanical engineering and computer science. Radio astronomy studies the physical Universe as a laboratory for fundamental physics. Understanding the resulting observations requires a knowledge of the gravitational and electromagnetic forces of nature, particle physics, solid-state physics, and special and general relativity. This has led to the discovery of totally new and unpredicted radio phenomena such as the Cosmic Microwave Background, interstellar ionized gas and plasmas, as well as pulsars, quasars, and black holes. These and other observational discoveries have totally changed our understanding of the Universe and our place within it, which has captured and excited the imagination of the general public.

From these observations, it has been possible to study in detail the origin of the Universe (the Big Bang model), and the evolution of galaxies, clusters of galaxies, stellar populations and planetary systems, such as our own solar system. It has provided validation checks of fundamental physical theories such as general relativity, and produced an almost perfect (inertial) reference frame for all kinds of terrestrial geographical surveys and for ultimate timekeeping purposes. Radio astronomy offers, as one of the most accurate geodetic techniques, a way to monitor the motions of tectonic plates, Earth tides, polar motion, and variations in the length of the day.

C.2 The radio astronomy service

The Radio Regulations (RR) define the following:

"1.13 *radio astronomy:* Astronomy based on the reception of *radio waves* of cosmic origin."

"1.5 *radio waves or hertzian waves*: Electromagnetic waves of frequencies arbitrarily lower than 3 000 GHz, propagated in space without artificial guide."

Within this broad range of the spectrum, radio astronomy observations are conducted under the aegis of three radio services:

- the radio astronomy service;
- the space research service;
- the radiolocation service.

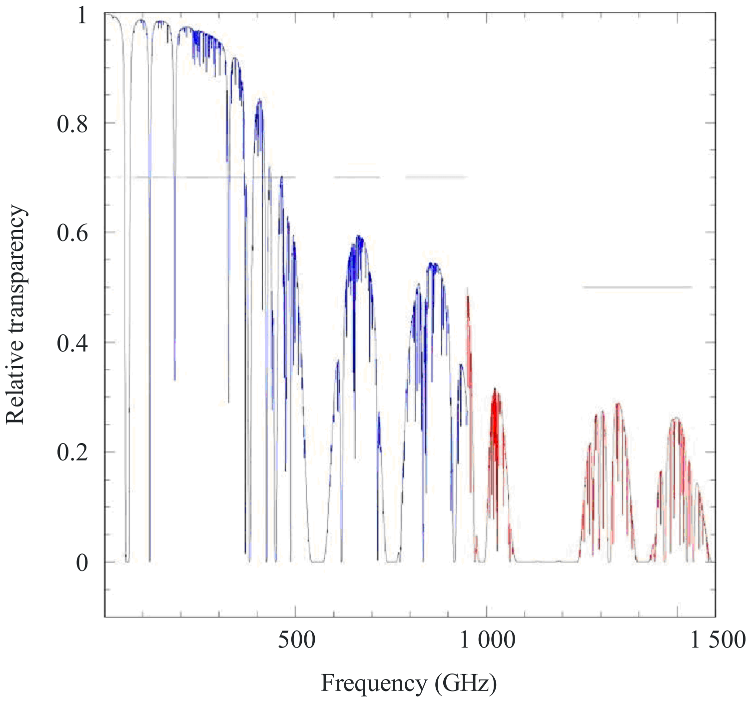
In addition to the above services used for radio and radar observations, space based radio astronomy requires bands for telecommand, communication and data transmission purposes. These functions are carried out under the aegis of the space research service (SRS-active – RR No. 1.55) and the space operation service (SOS- RR No. 1.23).

C.2.1 Spectrum and atmosphere

Ground based radio astronomy observations are conducted by the RAS between approximately 13 MHz and 2 000 GHz at all frequencies in the spectrum where the atmosphere is at all transparent.

The atmosphere is opaque below approximately 13 MHz (the actual cut-off frequency varies with the location, season, time of day and ionospheric conditions), but is transparent between ~13 MHz and 55 GHz, and above 55 GHz in a series of windows of decreasing transparency up to ~1 000 GHz. Some atmospheric windows, allow astronomical observations from a few high, dry places on the surface of the Earth up to ~2 000 GHz, (see Figs 1 and 2).

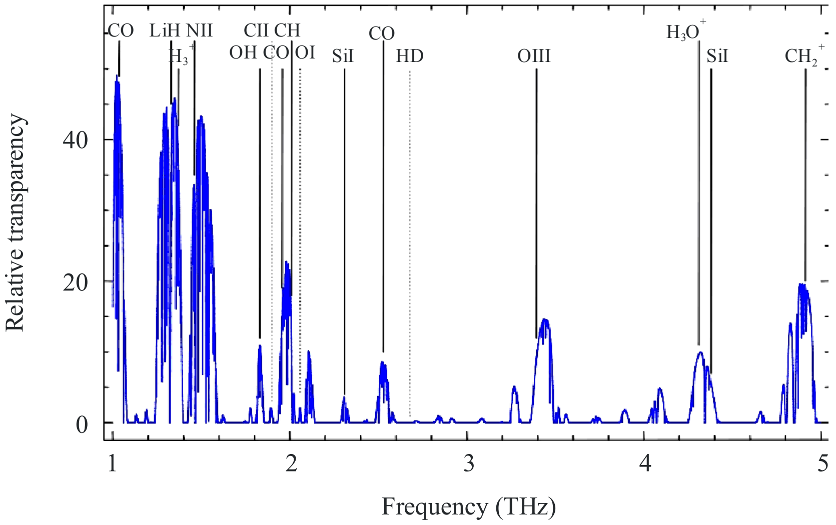
FIGURE C.1



Report RS.2178-C.01

Figure C.1 shows the atmospheric transmission up to 1.6 THz at Cerro Chajnantor in Chile, which is the site of the international Atacama Large Millimeter/submillimeter Array (ALMA), at approximately 5 000 m altitude in the high and extremely dry Atacama Desert. This site is considered to be one of the best sites for millimeter/submillimeter astronomy on Earth.

FIGURE C.2



Report RS.2178-C.02

Figure C.2 shows the zenith transmission between 1 and 5 THz at an even higher astronomical site, near the location of ALMA. Above 2 THz the atmosphere is essentially opaque, except for a few windows. Even at this high and extremely dry site, transmission at the zenith barely rises above 10% in any of the atmospheric windows.

C.2.2 Need for multiple frequency bands

Radio astronomers are interested in obtaining as complete information as possible about the properties of the sources observed. This requires observation of the frequency, intensity, polarization, position on the sky as well as temporal and spatial variations of electromagnetic radiation. Complete characterization can only be obtained by observing sources in a variety of spectral regions, which is the primary reason why astronomers need access to many well-positioned frequency bands.

Cosmic radio emission may be classified broadly into two categories: continuum and spectral line emission:

– Continuum emission is characterized by a smooth variation of intensity with frequency over a broad spectral range; it may be generated by a number of mechanisms. Radio astronomers are interested in identifying these mechanisms in order to obtain information about the physical conditions in the source. To do so, the emission must be sampled, preferably at frequency intervals of approximately an octave or closer, although the exact frequency at which an observation is made is not important.

– Spectral lines, on the other hand, originate in nuclear, atomic or molecular transitions that occur at specific, fixed frequencies, and observations must be made at those frequencies. Their frequencies can be calculated and predicted on the basis of physical principles. In general, line emission is not detected at exactly its predetermined frequency because all observed emission sources are in motion relative to the solar system, our galaxy, and to the Universe. These motions result in a shift in the line frequency because of the Doppler effect, which is called a redshift for motions away from the observer and a blueshift for the (few) sources moving towards the observer. In particular, recession velocities in the expanding Universe increase with distance and may become so large that substantial shifts towards lower frequencies occur from distant sources. Searches for the 1 420 MHz neutral hydrogen (HI) line, for example, have been carried out at frequencies as low as 150 MHz.

Radio astronomy allocations reflect these science requirements, to the extent possible. The sensitivity or minimum detectable signal of a radio astronomy observation is inversely proportional to the square root of the observed bandwidth and integration time used[15]. Radio astronomy signals are extremely weak, and most bands allocated to the RAS are relatively narrow. Quite often, continuum observations can not be carried out within a reasonable amount of time, when a high sensitivity level is required and when only the relative narrow frequency bands allocated to the RAS are used.

In addition to this, thousands of spectral lines have been observed, or predicted as observable, so, allocations can only be made for a few of the astrophysically most important lines. These are listed in Recommendations ITU-R RA.314 and ITU-R RA.1860. In some cases interesting spectral lines have been discovered in bands allocated to other services. For example, the spectral line of methanol at 12.718 GHz is in the middle of a band allocated to various active services, including the broadcasting-satellite service (BSS), and can only be observed on an opportunistic basis without interference from other spectrum users. In addition, many of the spectral lines of interest to astronomers are Doppler shifted to a region of the spectrum where no radio astronomy allocation exists. For all these reasons, radio astronomers are often forced to observe outside radio astronomy bands, where they must mitigate the risk of encountering interference.

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[15] See Chapter 4 of the ITU-R Handbook on Radio Astronomy, Geneva, 1995 for a derivation.

The face-on galaxy NGC 6946 is shown in the visible(left) and in neutral hydrogen (HI) line emission (right) at 1 420 MHz, on the same scale. The neutral hydrogen emission shows large-scale spiral arm structures that extend far beyond the optical image and reveal the dynamics of the galaxy. At many locations (particularly the 'holes' in the distribution) high-velocity gas outflows relate to ongoing star formation. Radio data from the Westerbork Synthesis Radio Telescope, The Netherlands.

Figure C.3 illustrates the differences that can be observed between optical and radio images of galaxies. While the optical image traces mostly stars, the radio image provides far better information about the extended structure and dynamics of the gas in the galaxy.

FIGURE C.3[16]

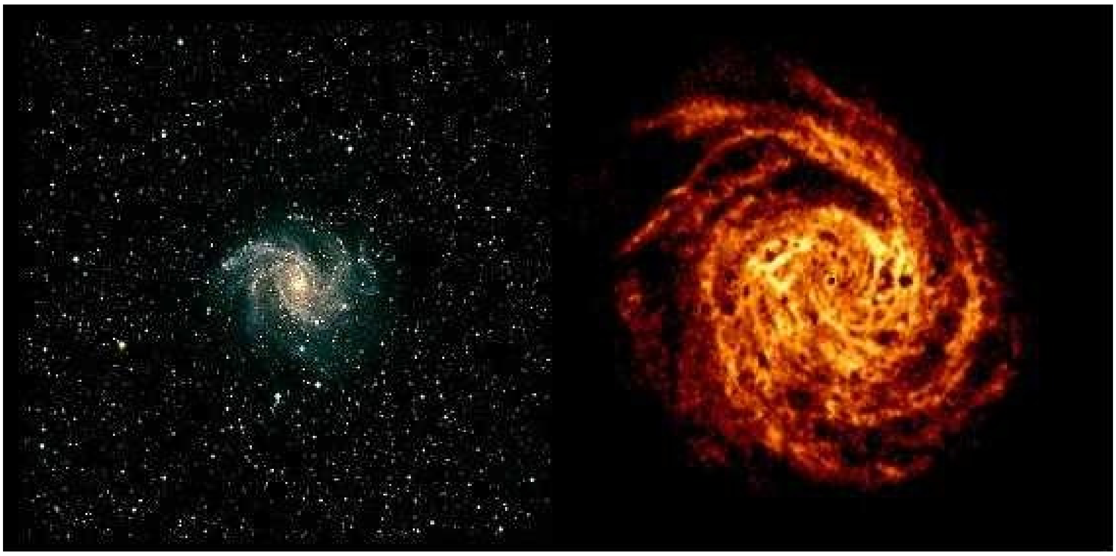

Figure C.4 illustrates the appearance of the plane of our Galaxy, as it appears (from top to bottom) in the 408 MHz radio continuum radiation, the 21-cm HI spectral line, and the optical part of the spectrum. The dark regions are caused by light-absorbing dust structures.

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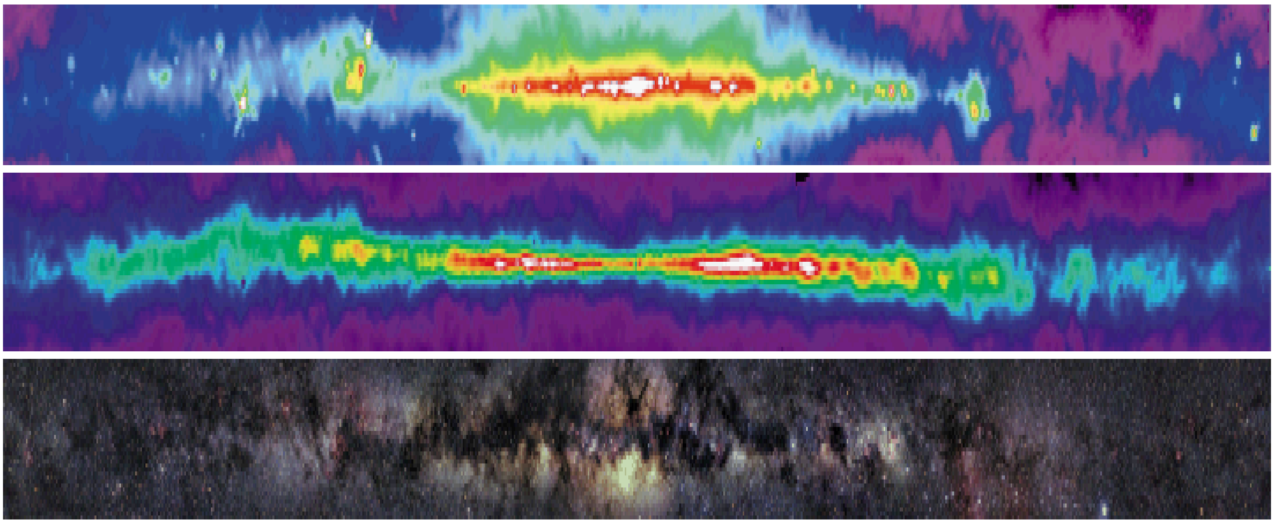
[16] BOOMSMA, R., OOSTERLOO, T. A., FRATERNALI, F., VAN DER HULST, J. M., SANCISI, R. [2008] Astronomy and Astrophysics.

FIGURE C.4



Source: NASA

C.2.3 Radio astronomy sites

As noted above, radio waves of natural origin are extremely weak and their detection requires large collecting areas (antennas) and the most sensitive receivers. This sensitivity, and the fact that radio astronomers are often forced to observe outside radio astronomy bands, increases the interference potential for a passive operation. The combination of frequencies fixed by nature and weak signals requires a well-protected observing environment.

As a result, most radio astronomy operations have been placed away from major metropolitan areas. Nevertheless, these very high sensitivity instruments have become increasingly vulnerable as a result of increased spectrum use and the expansion of commercial operations into new frequency ranges.

The central plane of our Galaxy with the Galactic Centre in the middle. The upper frame shows the radio continuum structure at 408 MHz. The middle frame shows the integrated neutral hydrogen emission at 1 420 MHz. The lower frame shows the central region in optical light and displays the dark dust structures.

The locations of new generation radio telescopes are carefully chosen to reduce the impact of man-made noise. The selection process for the Square Kilometer Array (SKA) telescope for example is largely based on remoteness. Similarly, the location of the Atacama Large Millimeter/sub-millimeter Array (ALMA) telescope in the high Andes in Chile was based on its height and remoteness of this site. The lowest frequency receiver band planned for ALMA is at ≈30 GHz. This band has the highest sensitivity and must be protected with the greatest care.

Geographical sharing of frequencies for ground-based operations are only possible when appropriate coordination distances are used: these have to be determined using terrain dependent propagation models.

C.3 Space research service

The SRS uses spectrum to explore outer space for scientific purposes using satellite platforms. This exploration covers studies ranging from the structure and history of the Universe and its dynamics to that of our solar system.

Space research applications require data links between ground stations and spacecraft stations orbiting around the Earth or travelling across the solar system. The ground stations often use antennas with very high gain, and transmitters with high power or receivers with high sensitivity. Observational capabilities of space research satellites have frequencies ranging from microwaves to X-rays, including in particular far infra-red, infra-red, optical and ultra-violet. They cover spectral ranges that are not at all or at best only partially accessible from the Earth's surface.

The space agencies (NASA, ESA, JAXA, and those of China, India and Russia) have their networks to support interplanetary spacecraft missions and radio and radar astronomy observations for the exploration of the solar system and the Universe. These networks also support selected Earth-orbiting missions.

Below 5 MHz and above 2 000 GHz, and in selected regions in between, the atmosphere is opaque to radio waves at all times from everywhere on Earth. At those frequencies, radio astronomy observations must be conducted from space in bands allocated to the SRS (passive) – RR No. 1.55. Very Long Baseline Interferometer (VLBI) observations may also be conducted from space, usually in combination with observations from the ground. These space VLBI observations provide angular resolutions equivalent to that of a telescope of diameter several times the radius of the Earth, and thus produce the highest possible angular resolution for radio observations of celestial sources.

C.4 Radar astronomy

Radar astronomy differs from radio astronomy as it involves both the transmission and reception of radio waves. Only objects in the solar neighbourhood can be studied with radar techniques because of the two-way spreading loss. Such measurements are used to determine the properties e.g. surface features and roughness, shape, rotation rate, and reflectivity of the target sources, e.g. planets, moons, asteroids and even interplanetary dust. Only radar astronomy makes it possible to detect small-scale space debris.

In spite of the generation and transmission of very large amounts of power, typically in the megawatt range, radar astronomy requires interference free bands, just as radio astronomy does, because of the large interplanetary distances, and because the received spectral flux-density detected at the Earth varies with the inverse fourth power of the distance, radar astronomy is carried out in bands allocated to the radiolocation service (RLS – RR No. 1.48), which therefore must be shared with other active systems. It is consequently carried out in a limited number of bands, e.g. at 2 380 MHz and 8 560 MHz.

At the present time there are only four radar astronomy sites: Arecibo Observatory (Puerto Rico), Goldstone Observatory (USA), FHR[17] (D) and Evpatoria Observatory (Ukraine). Successful bi-static radar observations have been carried out involving these dishes as transmitters while using other radio telescopes to detect the reflected signals, as for instance between the Arecibo radar and the Green Bank Telescope (USA), and between the Evpatoria radar and the Medicina telescope (Italy).

A typical application of radar astronomy is the detection and tracking of near Earth objects (NEO's), meteorites and asteroids that may come close to or collide with the Earth. Radar astronomy is one of the few options available to detect and track NEO's and offers probably the most comprehensive way to study them. When used in this capacity, radar astronomy may be considered as a disaster prediction and prevention service on the planetary scale.

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[17] FHR: Fraunhofer Institut für Hochfrequenzphysik und Radartechnik.

This radar technology is also used to detect space debris in orbit around the Earth, thereby enabling satellite operators to move their space vehicles away from potential collisions. It is the only way to study the density of space debris of less than approximately 1 cm size.

The same radar astronomy imaging techniques (for the near field) are used for civil and military purposes for imaging spacecraft in orbit.

C.5 Space operation service

The spectrum used by the space operation service enables the operation of spacecraft and the retrieval of data taken by them, which is an indispensible function for carrying out space-borne science.

The space operation service spectrum allocations, which can be used for controlling and monitoring any space system, can therefore be used for scientific space applications, as well as for other telecommunication space applications. However, it is to be noted that the ITU RR require the use of telecommunications bands for controlling and monitoring of a satellite during normal operations. The use of these bands for space telecommunication services is therefore normally limited to the Launch and Early Orbit Phase and to emergency situations.

C.6 Passive techniques

The passive observation technique (passive sensing) implies the measurement of naturally occurring radiation, usually of very low power levels, which contain essential information about the physical process under investigation; it involves the use of receive-only techniques, with no transmitters involved.

All material compounds with non-zero temperature (on the Kelvin scale) continually radiate broadband electromagnetic energy (see Fig. C.5 for a continuum radio image of the centre of our Galaxy). Furthermore, each molecule and atomic species has unique frequency characteristics that can be recognized from its predetermined spectral signature (see Fig. C.6). Radio astronomy has no control over the naturally generated radio signals that need to be detected. Consequently, there are no alternative spectral options available for these specific measurements; these frequency bands are therefore an important natural resource that requires protection.

Of particular interest are radiation peaks indicating the presence of specific molecular species, or the absence of power at certain frequencies indicating the absorption of the background signals by interstellar or atmospheric gases. The strength or absence of signals at particular frequencies is used to determine whether specific gases are present, together with their physical parameters (abundance, temperature, density, exciting radiation fields).

Even extremely low levels of interference received at the input of a radio astronomy receiver may degrade observations since most receivers are unable to discriminate between natural and man-made radiation.

Among the numerous ITU RR footnotes relating to the science services, two recognize the frequency bands used by passive services:

– RR No. 5.340[18] lists a number of essential frequency bands in which all emissions are prohibited. It offers the passive services protection to deploy and operate their systems in the most critical frequency bands;

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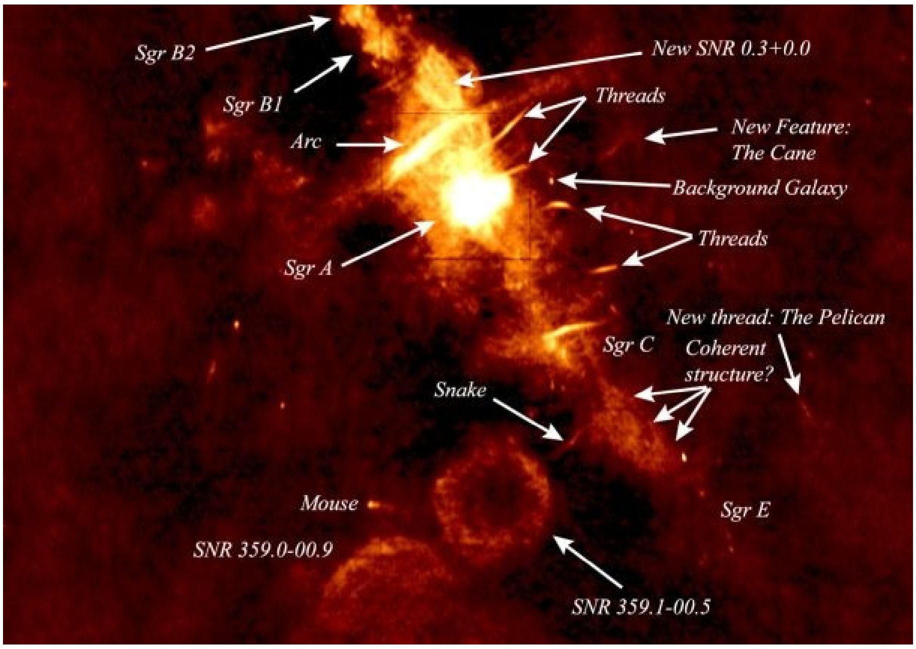
[18] The RR No. 5.340 states that “All emissions are prohibited in the following bands”, followed by a list of frequency bands.

– RR No. 5.149 urges administrations to take all practicable steps to protect the radio astronomy service from harmful interference in a number of specific frequency bands;

FIGURE C.5[19]



The radio continuum structure of the centre of our Milky Way galaxy. This high-resolution radio continuum view made at 327 MHz covers a 4x4 degree region using the telescopes of the Very Large Array near Socorro, New Mexico, USA. The galactic centre itself is at the edge of the extremely bright object labelled Sagittarius (Sgr) A, suspected of harbouring a million solar mass black hole. Along the galactic plane, which runs diagonally through the image, are complex clouds of gas energized by hot stars and circular-shaped supernova remnants (SNRs) – hallmarks of a violent and energetic cosmic environment. But perhaps most intriguing are the arcs, threads, and filaments which abound in the scene. Their uncertain origins challenge present theories of the dynamics of the galactic centre.

C.7 Economic and societal value

C.7.1 Introduction

The societal and economic value of the use of spectrum has become an increasingly important criterion for spectrum management. Several countries around the world have made major investments in the use of spectrum for radio astronomy and space research purposes. As § A.4.2 of this Report notes, it is not appropriate for science applications to define the economic value by simply adding up the quantified costs and benefits, and compare the result with costs and benefits of alternative spectrum use. Beside such considerations, one must also consider the spin-off aspects of radio astronomy and space research activities on other economic sectors. The technical innovations that were specially developed by radio astronomical and space research have often been implemented directly or indirectly in many widespread technological applications, which benefit society as a whole, even though they are inherently difficult to quantify monetarily.

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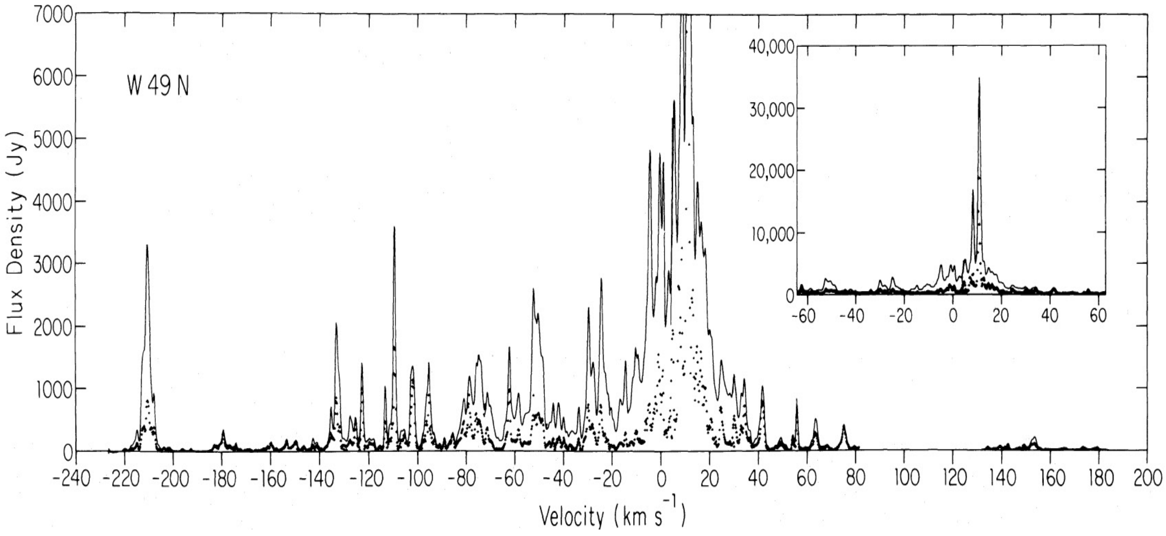
[19] N. E. Kassim, D. S. Briggs, T. J.W. Lazio, T. N. LaRosa, J. Imamura, 2002, produced at the Naval Research Laboratory [Kassim *et al.*, 1999; LaRosa *et al.*, 2000].

FIGURE C.6[20]



A spectrum of the water vapour (H_2O) maser line emission at 22.235 GHz from the Galactic star-forming region, W49N, in June 1978. The solid line represents the total power spectrum obtained with a single-dish telescope and the dotted profile represents the line emission from discrete point sources in the region observed with a Very Long Baseline Interferometer (VLBI) system using only three antennas (in the early days of VLBI). It should be noted that each feature in the spectrum represents emission from separate regions in W49N. Besides the total of 376 separate components found, there are many more features at lower flux levels. The inset presents the central part of the spectrum with a 10 times larger scale.

C.7.2 Investment in radio astronomy

A number of countries around the world have a long history in radio astronomy and have made substantial investments in ground and space based radio astronomy. It is difficult to estimate the amount of investment made by these countries for several reasons:

– Construction of a radio telescope usually takes several years, (sometimes 8-10, or more) and figures on investment are usually given in "as built" totals, not in current year Dollars or Euro's.

– A portion of the real cost is hidden or is simply not mentioned in the final amount. Some hidden costs involve design and development work that began years and sometimes even decades before a telescope was built. For example, the planning for the currently most expensive telescope project, ALMA, started in the early 70s, but only the expenses incurred since the official start in 1998 have been counted towards the project cost. Other hidden costs, e.g. graduate student labour, or the many unpaid work hours of astronomers and other professionals around the world, are not included in the project cost.

– Generally it takes several years for a telescope to reach its full potential as the initial receiver capability does not cover the full range of frequencies of the fully developed instrument. Costs incurred after commissioning are usually not included in the initial capital cost of the telescope, even though they may be substantial.

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[20] From WALKER, MATSAKIS and GARCIA-BARETTO *et al.*, 1982, Astrophysical Journal, 255, 128.

- Many telescopes make use of material available for free. These cost savings may be difficult to assess and are often not included. The first radio telescopes built after World War II made use of military radar dishes and other military surplus equipment. As a more recent example, the Combined Array for Research in Millimeter-wave Astronomy (CARMA; 2007) uses the elements of two pre-existing arrays: the Owens Valley Radio Observatory (OVRO) Millimeter Array and the Berkeley-Illinois-Maryland Association (BIMA) Array.
- Existing telescopes often undergo upgrades over time, and the cost of such upgrades may be substantial, but is not always included in the cost of the telescope.

Taking into account the above, only approximate estimates can be made for investments in radio astronomy facilities. US capital investment in radio astronomy facilities during the last 20-30 years amounts to approximately 3 000 million US $ (2009). In the rest of the world, capital investment in radio astronomy during the same period amounts to approximately the same.

The operating costs for these facilities are also not easy to obtain. By using the (pretty good) rule of thumb that the yearly operating cost of a facility is approximately 10% of its capital cost, one can nevertheless arrive at an estimate of perhaps twice the capital cost of these facilities over a 20-30 year period.

An educated guess for the future is that the next 20-30 years will see a similar figure for worldwide capital expenditure on RA, and probably similar operating costs as well. There will be two differences with respect to the previous period:

- capital investment is probably going to be split three ways, between the US, Europe and the rest of the world (most conspicuously Australia, China, Japan and South Africa) rather than more or less equally between the US and the rest of the world;
- most of these funds are going to be invested in international mega-facilities, rather than in smaller facilities.

As a conclusion: governments do invest a very considerable amount of public money in radio astronomy. Such support for radio astronomy in the past 2-3 decades, as well as the support expected in a similar period in the future, is in the 10 to 20 thousand million (10-20 billion) US $ range, and this may well be a conservative estimate.

C.7.3 Economic and societal value of radio astronomy research

The capital investments made in establishing radio observatories are only the first steps towards further economic activity.

It should be noted that radio astronomy is an integral part of astronomical research and provides information that is complementary to astronomical research at all other wavelengths. Therefore, researchers utilize radio observations in addition to those at other wavelengths. The “open skies” policy of radio observatories means that these instruments are accessible for all researchers from around the world and their students. Since each observing project generates at least three months (an underestimate) of work for analysis, interpretation and reporting, this indirect activity also adds up to a significant economic factor.

Progress in radio astronomy is driven by advances in receiver and digital technology. As a rule, the instrumentation of radio astronomy telescopes represents the most advanced technology that exists at any given moment, and radio astronomers play a very active role in pushing this technology to its ultimate limit in order to advance their scientific objectives.

The technical requirements of radio astronomy have directly or indirectly fostered technological innovations with very wide applicability in various areas that benefit the general public.

The economic value of such spin-off activities is difficult to estimate because they are part of the activities of multiple large corporations. For instance, the spin-offs of radio astronomy receiver research (see § C.7.3.1) can be found in specialized telecommunication equipment as well as in mass-produced consumer applications. Similarly it is difficult to estimate the economic and societal effects of medical imaging algorithms that are derived from radio astronomical imaging techniques (see § C.7.3.4). A clear global picture for such activities is not yet available.

The following sections present examples of the application of radio astronomy research activities in other areas of science:

C.7.3.1 Telecommunication technology

- **Receiver systems**: Radio astronomy receiver systems include high-gain antennas, low-noise receivers, solid-state oscillators and frequency multipliers. The development of parametric amplifiers, cryogenically cooled GaAs FET amplifiers, HEMT amplifiers and SIS mixers were all motivated or strongly influenced by radio astronomy requirements. These developments resulted in receiver temperatures as low as 4 Kelvin and centre frequency sensitivities extending from a few MHz up to 1 500 GHz over extremely wide bandwidths. The lowest noise temperatures reached show that one is now working close to the quantum limit of what is technically possible. This technology is also used in some of the most sophisticated telecommunication systems.

  The local oscillators are synchronized in time at sub-picosecond levels using atomic frequency standards located at radio telescope sites spread worldwide. These frequency standards are used as a backbone system for timekeeping for terrestrial and space navigation systems.
- **Homology principle**: One of the major difficulties in the construction of large steerable parabolic antennas with precise reflecting surfaces is the detrimental effect of gravitational deformation that changes the shape of the antenna as it is moved from one position to another. This problem was solved in 1967 through the so-called homology principle[21]. An antenna designed according to the homology principle does deform under gravitational stress, but does so into another paraboloid with a different focal position and length. By keeping track of the focal position, the effects of gravitational deflection can be minimized by shifting the position of the feed to the new focal point, thus minimizing the loss of signal. The designs of all recent large reflector antennas take advantage of homology to some extent, and homologous design has become even more important in the millimeter wavelength range.
- **Antenna technology**: Radio astronomers were the first to use circularly polarized feed horns. This technical development subsequently enabled satellite transmitters to transmit both polarizations independently using the same feed horn.

C.7.3.2 Interferometric technology

Radio astronomers produced the first digitized single-pixel surveys of the radio sky using interferometry.

- **Interferometry**: Electromagnetic waves emanating from a source have a complex wave pattern which is dependant upon the extent of the source, and which, in the absence of any obstructions, expand outwards from the source. When at some distance from the source, the signal generated by the expanding waves in two separate antennae (separated by some distance from each other) are combined (multiplied) together, an interference or fringe pattern is produced. The detailed form of this interference pattern is dependant upon the

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[21] Von Hörner, S.: “Design of large steerable antennas”, The Astronomical Journal, **72** (1967), 35.

structure of the source, its position, and the separation of the two antennae. It is possible to reconstruct an image of the source by making measurements of the fringe patterns for different antenna spacings. The result of this wave reconstruction technique is an image of the source with a resolution that depends upon the ratio of the maximum separation of the antennae divided by the operating wavelength. This technique is called interferometry; it is an important investigative technique in the fields of astronomy, fibre optics, engineering metrology, optical metrology, oceanography, seismology, quantum mechanics, nuclear and particle physics, plasma physics, and remote sensing.

Astronomers were the first to develop image reconstruction and cleaning techniques for removing (most) instrumental and environmental effects from images. These methods are used for terrestrial and satellite-based surveys of the heavens and for EESS surveys of the Earth.

In the latter part of the 20th Century, such radio interferometric systems were widely used for facilitating automatic landing of aircraft. The same type of technology is now being used to locate cell-phone users, to offer targeted marketing and location-related services, including rapid response to accident sites by emergency services. A very prominent example of an interferometric system is the wireless network Wi-Fi.

– **Wi-Fi applications**: In the development of wireless connections between computer terminals, reflections caused a major difficulty, as a transmission would arrive at a receiver followed by a series of echoes. This problem was well known to radio astronomers, who had developed signal processing techniques to overcome comparable issues caused by reflections in the atmosphere. As a result, radio LANs send the information at different frequencies and recombine the signals at the receiver in the same manner as in radio astronomy.

– **Navigation**: Over the ages astronomy has delivered major contributions to navigation including that of spacecraft. The development of *radio sextants* for marine navigation has allowed accurate determination of positions at sea even on overcast and rainy days. A recent application of radio interferometry is its use for emergency position determination of mobile phones, which is done using multilateration based on the signal strength to nearby antenna masts. Multilateration positioning locates an object by accurately computing the time difference of arrival (TDOA) of a signal emitted from that object to three or more receivers. It can also be used to locate a receiver by measuring the TDOA of a signal transmitted from three or more synchronized transmitters.

C.7.3.3 Computing technology

Radio astronomers have developed state-of-the-art digital techniques to correlate and record telescope data. Modern high-power (parallel processing) computer arrays are then used to process the extremely large amounts of data collected by radio interferometers. Simultaneous multi-beam synthesis, real-time mitigation of RFI, and reconstruction of complex radio source structures are examples of such modern processing capabilities. This made radio astronomy data processing into a test case for data-network capabilities, computer languages and computing software usable elsewhere.

– **Computer language FORTH**: A highly visible spin-off of radio astronomy is the computer language FORTH (or Forth) developed at the USA NRAO in the early 1970s. The first application of Forth was the control and data processing for one of the NRAO telescopes. The Forth language has now been used in many applications, such as the first hand-held computers carried by Federal Express delivery agents, and continues to be used today in its evolved forms. Other applications include satellite tracking software, and simulation software for the Canadian-built 50-foot long six-joint arm carried on the Space Shuttle for use in satellite deployment and retrieval operations and to assist astronauts in servicing tasks (e.g. the recent mission to repair and upgrade the Hubble Space Telescope) and many others[22].

C.7.3.4 Medical technology

Radio astronomers initiated the mathematical techniques that allow the reconstruction of two-dimensional images from one-dimensional scans and the reconstruction of three-dimensional volumes from two-dimensional images[23] (Bracewell and Riddle, 1967). Radio astronomy image reconstruction techniques have been incorporated into modern Computed Tomography (CT) scanning, Positron Emission Tomography (PET) scanning, and magnetic resonance imaging. Radio observations of distant cosmic sources are basically measures of the temperature of these sources and the technique has been adapted to conduct non-invasive measurements of human tissue temperature.

Computed Tomography (CT): is a medical imaging method employing tomography created by computer processing. Digital geometry processing is used to generate a three-dimensional image of the inside of an object from a large series of two-dimensional X-ray images taken around a single axis of rotation.

Malignant tumours appear on microwave images of deep tissue as regions of anomalous temperature and can be readily detected. Microwave thermography is used with a true-positive detection rate of 96% to detect breast cancer.

– **Skin cancer**: One of the challenges facing astronomers studying stars and galaxies is to extract meaningful information from the jumble of signals. They therefore developed algorithms for picking out the weak signals from the background of random "noise". These algorithms helped astronomers to pinpoint thousands of faint X-ray sources and analyze their structures in a quantitative way.

  This technique has many applications where vital data might be buried in the background noise. In collaboration with medical doctors, and with the support of the German Space Agency, radio scientists developed a system for the early recognition of skin cancer. Small differences in colour can lead to the detection and measurement of the irregular cell growth associated with malignant melanoma, a particularly virulent form of skin cancer.

– **Digital radiography**: Digital imaging technology was developed to assist in measurements of X-ray emissions from galaxy clusters, important to astrophysicists in developing theories related to cosmology and the early evolution of the Universe.

  This technique was used in the design of a new digital radiography system to improve efficiency, flexibility and cost-effectiveness in hospital radiographic examinations and reduces hospital and emergency room operating costs by eliminating the expense of film in X-rays and other image acquisition procedures. With this technology, patient radiographic examinations are conducted in the standard manner except that body images are not recorded on film, but the image is stored in the computer's memory. The doctor (and/or patient) can then view the X-ray images immediately without waiting for photos to be developed.

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[22] For more complete information on the uses of Forth, see, e.g.: (http://www.forth.com/index.html).

[23] Bracewell, R.N. and Riddle, A.C.: "Inversion of fan beam scans in radio astronomy", *Astrophys. Journal*, **150**, 427.

C.7.3.5 Time and frequency standards

The VLBI community has, of necessity, developed the most stable and precise time standards and time transfer methods for their VLBI measurements. Astronomers require the most accurate and precise time and atomic frequency standards (uncertainty levels of few parts in 10^{-16} s). These precise timing systems have later been developed commercially and are now used for space communication and satellite navigation and defense purposes. The RNSS systems (GPS, Glonass, Galileo), that are used worldwide, have their time and coordinate systems tied to the Earth and to the cosmos by the maintenance activities of the International VLBI Service for Geodesy and Astrometry (IVS).

Accurate man-made clocks ushered in the modern era of safe navigation. The quest for ever more accurate clocks continues in the work of the International Time Bureau, and its determination of time from an ensemble of atomic clocks. The best independent check on the long-term stability of the international atomic time standards comes from the timing observations of millisecond pulsars by radio astronomers. These are conducted on an ensemble of the most stable pulsars to minimize any effects of secular changes in the electron content of the interstellar medium or in the behaviour of individual pulsars, and, independently, by fitting the timing observations of millisecond pulsars in binary stellar systems to the orbital parameters of the system.

C.7.3.6 Earth observation

Radio astronomy interferometric methods have been adopted to develop *passive remote-sensing* techniques for measuring the temperature of the Earth's atmosphere, surface properties, and the distribution of water vapour, cloud water content, precipitation, and impurities such as carbon monoxide.

The detection of forest fires by their microwave radiation is based on the same technical principle.

These techniques, their applications and benefits for society are comprehensively described in Part A of this Report.

C.7.3.7 Geodesy

Although the VLBI technique was developed as a tool to gather data on the detailed structure and positions of astronomical sources, it also has applications in many other fields of research. Thus the extremely accurate VLBI positions of distant quasars and radio sources also provide the most accurate spatial reference frame in existence. Using celestial sources as reference points, terrestrial VLBI measurements are used to measure motions on Earth, e.g. to measure continental drift, and to estimate the likelihood of Earthquakes, through highly accurate measurement of slippages of tectonic plates at fault lines. The International VLBI Service for Geodesy and Astrometry (IVS) was established to provide services in support of geodetic, geophysical, and astrometric research and operational activities[24]. Terrestrial VLBI techniques and accurate Doppler tracking are also being used for high-precision space-navigation within our solar system such as for the recent landing of the ESA's Huygen's probe on Titan, the largest moon of Saturn.

C.7.3.8 Mining technology

The imaging techniques described above (§ C.7.3.4) are also directly applied to the sub-surface exploration for oil and mineral deposits, by processing data from a chain of small surface explosions, as received by an array of seismometers.

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[24] See: http://ivscc.gsfc.nasa.gov/html.

C.8 Trends in radio astronomy

Current trends in radio astronomy are towards even higher sensitivity at all frequencies. Since current receivers are reaching the quantum limit and cannot be further improved, there is a drive towards larger collecting areas and the use of broader operational bandwidths. Existing telescopes are being upgraded to accommodate broadband (up to 1-8 GHz depending on frequency) receiver systems for both continuum and spectral line observations. Some international effort is underway to construct new generation radio telescopes with significantly larger collecting areas.

Examples are:

1. the square kilometer array (SKA) project, which seeks to build a giant radio interferometer network with a total collecting area of a square kilometer and baselines up to 3 000 km operating in the 100 MHz – 25 GHz frequency range;
2. the low frequency array (LOFAR) in The Netherlands and neighbouring countries; a radio interferometer network with a total collecting area of 100,000 m^2 and baselines up to 1 000 km operating in the 30-250 MHz frequency range; and
3. the Atacama large millimeter array (ALMA) with 64 antennas operating from 30 to 850 GHz on a 5 km high plateau in the Andes.

In the development process towards larger sensitivities, the actual use of frequencies will not change significantly. The existing bands allocated to the RAS that enjoy a protected status will continue to be used for long-time integrations to detect weak signals of interest and for calibration. The continuation of the protection of these bands, which have been chosen for physical reasons and for the presence of important spectral lines, is essential for the continuation of radio astronomical research in a large number of key areas.

C.9 Conclusions

The use of spectrum by the radio astronomy service and the space research service has considerable societal weight and economic value. However, it is very difficult to quantify the benefits of such use as they relate to society as a whole, are often hidden in applications used in other technologies, may only be realized over very long periods of time, and may be difficult to foresee.

Many administrations recognize the benefits, which this science brings to society, and therefore continue to invest in radio astronomy and space research.

Investments made during 2009 in existing facilities exceed those made to establish the facilities.

On a worldwide collaborative basis, large investments are being made and/or foreseen for international facilities such as LOFAR, ALMA and the SKA.

The radio astronomy and space research services have developed technologies, which have found applications in various other fields, such as medicine, telecommunications, time and frequency standards, Earth observation, computing, navigation, geodesics and mining.

Many of the scientific activities are organized at a global level and spectrum related issues must therefore be considered globally since unilateral decisions may have a worldwide impact on related frequency use and measurements.

Attachment

List of acronyms and abbreviations

ALMA	Atacama large millimeter/submillimeter array
AMSR-E	Advanced microwave sensing radiometer – EOS
BIMA	Berkeley-Illinois-Maryland Association
BSS	Broadcasting satellite service
CARMA	Combined array for research in millimeter-wave astronomy
CT	Computed tomography
CBD	Convention on biological diversity
CESRA	Community of european solar radio astronomers
CGMS	Coordination group for meteorological satellites
EESS	Earth exploration-satellite service
EOS	Earth observing system
EPS	EUMETSAT polar system
ESA	European Space Agency
EU	European Union
EUMETNET	The network of european meteorological services
GaAs FET	Gallium arsenide field effect transistors
GBT	Green bank telescope
GEO	Group on Earth observation
GEOSS	Global Earth observation system of systems
GHz	GigaHertz (= 1 000 000 000 Hertz)
GMES	Global monitoring for environment and security
GNSS	Global navigation satellite system
GOES-R	Geostationary operational environment satellite – R series
GOS	Global observing system
GPS	Global positioning system
HEMT	High electron mobility transistor
InSAR	Interferometric synthetic aperture radar
ITU	International Telecommunication Union
IVS	International VLBI service for geodesy and astronomy
JAXA	Japan Aerospace Exploration Agency
LAN	Local area network
LEO	Low Earth orbit
LEOP	Launch and early orbit phase

LOFAR	Low frequency array
MetAids	Meteorological aids service
Metsat	Meteorological-satellite service
NASA	National Aeronautics and Space Administration
NDACC	Network for detection of atmospheric composition change
NEO	Near Earth object
NOAA	National oceanic and atmospheric administration
NPOESS	National polar-orbiting operational environmental satellite system
NRAO	National Radio Astronomy Observatory
NRC	National Research Council
NSIDC	National Snow and Ice Data Centre
OVRO	Owens Valley Radio Observatory
PET	Positron emission tomography
RAS	Radio astronomy service
RFI	Radio frequency interference
RLS	Radiolocation service
SAR	Synthetic aperture radar
SIS	Superconductor insulator superconductor
SKA	Square kilometer array
SOS	Space operation service
SPENVIS	Space environment information system
SRS	Space research service
THz	TeraHertz (= 1 000 000 000 000 Hertz)
UNICEF	United Nations Children’s Fund
UNCCD	United Nations Convention on combating desertification
UNSDI	United Nations spatial data infrastructure
VLBI	Very long baseline interferometry
WMO	World meteorological organisation
WPR	Wind profiler radar
WRC	World Radiocommunications Conference
WSSD	World Summit on Sustainable Development
