Handbook

Earth Exploration-Satellite Service

English Edition 2011
Radiocommunication Bureau

THE RADIOCOMMUNICATION SECTOR OF ITU

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.

The regulatory and policy functions of the Radiocommunication Sector are performed by World and Regional Radiocommunication Conferences and Radiocommunication Assemblies supported by Study Groups.

Inquiries about radiocommunication matters

Please contact:

I T U
Radiocommunication Bureau
Place des Nations
CH-1211 Geneva 20
Switzerland

Telephone:	+41 22 730 5800
Fax:	+41 22 730 5785
E-mail:	brmail@itu.int
Web:	www.itu.int/itu-r

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PREFACE

The International Telecommunication Union (ITU) is the leading United Nations agency for information and communication technology issues and the global focal point for governments and the private sector in developing networks and services. The Radiocommunication Sector of the ITU (ITU-R) plays a vital role in the global management of the radio-frequency spectrum – a limited natural resource which is increasingly in demand from a large and growing number of services including science services such as the Earth Exploration-Satellite Service (EESS). The EESS makes use of specific frequency allocations as documented in the ITU Radio Regulations (RR). Use of EESS frequency allocations is further refined in the RS Series (for remote sensing) and the SA Series (for space applications, in particular for data communications to and from science satellites) of the ITU-R Recommendations, based on technical characteristics and operational procedures.

Historically, on account of its specificity, the development of EESS has been considered by a narrow circle of specialists. This stems primarily from the fact that the main users have been various security agencies or scientific institutions dealing with the fundamentals of space and the Earth. However, as a result of technological development in this sphere, science services are giving rise to a large number of applications for which there is significant demand, as they are indispensable and extremely important in humankind's quest to combat various natural and climatic disasters and mitigate their effects. In particular, it has been stated at the World Radiocommunication Conference 2007 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". At the same time, more and more applications, such as remote sensing imagery products, are emerging that respond to commercial demands.

This Handbook gives to readers a full and comprehensive information on development of EESS systems. Specifically, it provides basic definitions, sheds light on the technical principles underlying the operation of systems and presents their main applications to assist administrations in spectrum planning, engineering and deployment aspects of these systems.

François Rancy
Director
Radiocommunication Bureau

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FOREWORD

The Earth exploration-satellite service (EESS) is an integral part of our every day life. It does not show directly when you think about satellites, your first thought may be about your TV dish or the GPS receiver in your car, however the question is what would be life without the applications of the Earth exploration-satellite service.

It would be difficult to get precise weather forecast for instance, not because of the lack of meteorological images (they are part of the meteorological-satellite service) but because of the large quantity of information that are gathered by Earth exploration-satellite sensors. This data helps us to understand the dynamics of our atmosphere, its interaction with the ocean and land masses and thus are essential in building the prediction model that are used everyday in forecasting the weather. Long term effects on the climate can only be guessed from outer-space using active or passive sensors by measuring the wave height, the water temperature, the salinity, the ozone concentration – all kinds of data that capture the behavior of our environment.

It is a common statement to say that Earth has become a global village. You want to get somewhere you don't know, it is so easy to Google its location and discover the place, its topography just at the click of your mouse. Without satellites taking pictures of our entire planet and transmitting them every day that would not be possible.

The Earth exploration-satellite is also an essential tool in comprehending the enormous forces that makes Earth a living world. The geological features are clearly visible from space; even the ocean topography measured with centimeter accuracy mimics the relief of the ocean floor, revealing trenches and volcanic ranges.

Benefits to mankind in assessing biological resources, preventing natural disasters are just too common these days that it would be virtually impossible not to use them anymore.

This Handbook describes the ins and outs of the Earth exploration-satellite service, its technical characteristics, its applications, its spectrum requirements or lists its benefits for all of us on the good Earth. It will give the reader an excellent overview of the subject, references to the works done by the ITU will allow the interested reader to go further if needed.

As Chairman of the Radiocommunication Study Group 7* (SG 7), it is my great pleasure to present this Handbook to all interested people, and to the frequency management community at large who will, I am sure, find it an important reference tool in their own work.

The Handbook could not have been completed without the contributions from many administrations participating in SG 7. In addition to the many authors, special thanks should be given to Mr. John Zuzek (USA) as coordinator of the Handbook and the Chairmen of the two Working Parties that played an essential

* The Radiocommunication Study Group 7 (SG 7) for the Science Services was created through a structural reorganization in 1990 at the Düsseldorf CCIR Plenary Assembly. SG 7 comprises a number of Radiocommunication Working Parties (WP) that address technical issues related to specific disciplines under the umbrella of science services. The Earth exploration-satellite service falls within the remit of WP 7B and WP 7C concerning studies of the implementation and operation of meteorological passive and active sensors, from both ground-based and space-based platforms. As meteorology also depends on radio both to collect the data upon which its predictions are based, and to process and disseminate weather information and warnings to the public, this activity concerns WP 7B.

role in writing the various chapters, Mr Brad Kaufman (USA), Chairman of Working Group 7B on space radiocommunication applications and Mr. Edoardo Marelli (ESA), Chairman of WP 7C on remote sensing systems.

Special gratitude is also due to Mr. Alexander Vassiliev, former counselor of SG 7 and Mr. Vadim Nozdrin, the current counselor of SG 7 played an important role in the publication of the Handbook.

I hope you will find this publication interesting and beneficial just as I did, understanding the Earth is a long term project, for us and the next generations.

Vincent Meens
Chairman, Radiocommunication
Study Group 7

CHAPTER 1

INTRODUCTION TO THE EARTH EXPLORATION-SATELLITE SERVICE

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1.1 Overview

Earth exploration-satellite systems are used to gather data about the Earth and its natural phenomena. These satellites use active and/or passive sensors onboard the spacecraft to obtain data on the Earth's land, sea, and atmosphere for the purpose of studying and monitoring the Earth's climate and environment, amongst many other related scientific applications. Earth exploration-satellites used for weather-related purposes are known as meteorological-satellites (MetSats). MetSats can operate within the Earth exploration-satellite service or in their own more specialized service known as the meteorological-satellite service.

EESS satellites are frequently divided into two parts – the satellite bus and the payload. The satellite bus includes the physical structure of the satellite and all the systems needed to support the instruments carried on board. The instruments are called the payload and include sensors of one of two types, active or passive.

Active sensors are radar-like measuring instruments in the Earth exploration-satellite service which obtain information by transmitting radio waves and then receiving their reflected energy.

Passive sensors are very sensitive receivers in the Earth exploration-satellite service which measure the electromagnetic energy emitted, absorbed or scattered by the Earth's surface or atmosphere. In practice, they are instruments which measure the natural noise floor.

In addition to the data collected by satellites, data may also be collected from airborne or ground-based platforms to supplement and calibrate the satellite data. All of this collected data must also be transmitted to other platforms or to earth stations for additional processing and distribution.

The data from Earth exploration-satellites enable a diverse set of scientific applications which provide countless societal benefits to all humans. As a rule, the scientific data and the associated data products are shared with all nations, regardless of which nation built, launched, or operates the satellite. There are, however, a growing number of commercial remote sensing missions which sell their data; however, during a disaster situation, they share their data with disaster response agencies.

It should be noted that while "Earth exploration-satellites" is the terminology used in the ITU, the open literature will often refer to such satellites as "remote sensing satellites" or "Earth observation satellites". These terms are used interchangeably when discussing such Earth science applications.

1.2 Earth exploration-satellite system characteristics

Earth exploration-satellite system characteristics are described in subsequent sections. These include mission durations, orbits, satellite payloads, the communications subsystem, and the ground segment. The description of the satellite payloads includes a brief discussion of active and passive sensors.

1.2.1 Earth exploration mission duration and phases

Earth exploration-satellite missions have widely varying mission durations. Some EESS missions are purely experimental one-time missions while others are demonstration, prototype, or proof-of-concept missions preceding longer duration missions. The long duration missions are referred to as operational missions and such missions are routinely used in collecting data in day-to-day operations by various agencies.

As knowledge and understanding of the Earth's atmosphere, environment and ecosystems develop, new instruments are devised by the Earth science community. Such new instruments must be designed, built, flown, and tested to verify their performance and operational suitability before committing them to daily use by operational agencies such as weather services. Such demonstration missions may have an intended duration of only 3 years or less, but often are still useful for many more years if the instrumentation is robust, the spacecraft remains in good condition, and the operational need for mission data continues.

Operational EESS missions typically have design lives of 7-10 years or more, especially for those spacecraft using mature technologies. Most MetSat systems are operational systems that are intended to be operated for many, many years. Continuity of data is very important for such applications as climate studies and environmental monitoring, and operational satellites are replaced on a regular basis to maintain both coverage and data continuity. Some geostationary meteorological missions maintain spare spacecraft stored in orbit in a dormant (or back-up) state to enable the rapid replacement of a failed spacecraft.

The operating phases of Earth exploration-satellite missions occur after the development phase in which the satellite is constructed and tested prior to launch. Operating phases include pre-launch checkout, launch operations, transfer operations (wherein the satellite is moved from its intermediate post-launch orbit into its desired orbit), and on-orbit operations. Each operating phase requires specialized communication and tracking systems to be successful. Launch operations utilize precise ranging, command, and destruct systems during the critical launch phase and for contingency (i.e., emergency or anomalous/abnormal) operations. Transfer operations need command, telemetry and tracking data to ensure that the spacecraft reaches its proper orbit. On-orbit operations may require space-to-space communication between cooperative spacecraft, as well as communication direct to the ground for both command uplinks (forward links) and satellite data downlinks (return links).

1.2.2 Earth exploration mission orbits

Earth exploration-satellite systems normally operate in non-geostationary satellite orbits (NGSO). These orbits are typically circular with an altitude between 350 and 1400 km. Circular orbits are characterized by having identical apogee and perigee, i.e., the altitude of a spacecraft is constant relative to the surface of the Earth. Furthermore, most of these circular orbits are polar orbits that have inclinations near 90°. Polar orbits are used for Earth exploration-satellite missions that require coverage of every point on the surface of the Earth. Since the Earth rotates beneath the polar orbital plan, eventually every point on the Earth's surface will be visible to the satellite's instrumentation in a repeatable manner.

Many EESS systems operate in sun-synchronous orbits. Sun-synchronous orbits require that the satellite orbital plane remains fixed with respect to the sun-Earth line. Orbital inclinations are near 98° (called "polar", although technically near-polar). An important characteristic of these orbits is that the shadows observed in land-surface data are relatively constant, save for seasonal variations, thus making them particularly suitable for Earth observations and certain weather forecasting missions. Some sensors on these satellites observe the same place on the Earth every day, although at different viewing angles, while others will repeat observations with the same viewing angle but only after a longer (often more than 2 weeks) repeat period.

Several satellites carrying complementary instruments may be flown in a formation. Formation flying EESS satellites provide the capability to measure a portion of the atmosphere or surface of the Earth using both multiple instruments and multiple orientations. Measurements from such satellites are normally separated by an amount of time shorter than the time constant of the phenomena being measured. Typically this separation is on the order of 5 to 15 minutes, but can be as little as 15 seconds.

At present, two formations of EESS satellites are operating in NGSO orbits. In one formation, two or more satellites directly follow each other performing measurements of the same parcel of atmosphere or the Earth's surface at nearly the same time. In the other formation, a nadir pointing sensor conducts a measurement while another spacecraft conducts a near-simultaneous measurement at the limb of the Earth, thus measuring a much longer path through the atmosphere.

Geostationary orbits (GSO) form a unique ring around the Earth's equator at an altitude of 35 786 km. Satellites in this orbit have an orbital period that is equal to the period of rotation of the Earth (i.e., one sidereal day). A satellite in this orbit has a constant view of about one third of the Earth and can maintain continuous contact with an earth station located within its field of view. While the distance involved makes high spatial resolution more difficult, geostationary orbits provide unparalleled temporal resolution. Some MetSats are placed in GSO to obtain continuous coverage of weather patterns and storm systems occurring within the field of view of their various instruments.

1.2.3 Earth exploration-satellite bus functions

The satellite bus provides the platform which carries the instruments, or the satellite payload. The bus also provides the goods and services needed by the payload. Such goods and services include the provision of electrical power, communications to and from earth stations, data handling (sometimes together called C & DH, command and data handling), thermal control (heaters and/or coolers), attitude determination and control, and guidance and navigation. The communications systems are of particular interest to this Handbook.

A communications link from the Earth to a satellite is called a “forward” link or an “uplink”. Conversely, a link describing transmissions from a satellite to the Earth is called a “return” link or a “downlink”, regardless of whether it is the telemetry link or the science data link. These link definitions hold whether the link is direct between the earth station and the satellite or indirect through a data relay satellite (DRS) system.

Earth exploration-satellites have two types of communications systems. The first is the communication system whose function is tracking (locating the satellite), telemetry (downlinking the engineering data stream containing information about the status and health of the spacecraft and its subsystems, including the payload), and command (uplinking instructions to both the satellite bus and the payload). These functions are collectively called “TT&C”. The TT&C system provides communications for spacecraft operations. This communication system is discussed further in Chapter 2 of this Handbook. The second type of communication system provides the science data downlinks which transmit sensor data to earth stations. From these stations, the data can be routed, processed and distributed to various users. Although this communications system is supplied as a part of the satellite bus, it is of a different nature from the TT&C system and will be discussed separately. In some cases, the data stream is downlinked directly to users while in other cases the data stream is directed to central facilities for processing and later dissemination to the user community. More details on the science data downlink communication systems are given in Chapter 3 of this Handbook.

The locations of EESS earth stations depend upon the requirements for the particular Earth exploration-satellite mission as well as on physical, political and economic considerations. Communication and routing of data between EESS ground facilities are generally provided by terrestrial communication systems, although satellite links may also be used. When a satellite is in line-of-sight of an earth station and communication between them is possible, the occurrence is called a satellite “pass” or “contact”. The planning of operations during each pass requires managing the on-board data system, the satellite power system, and available communications capacity while guided by the observing goals of the mission. Various communications considerations will be discussed further in Chapters 2 and 3 of this Handbook.

1.2.4 Earth exploration-satellite payloads

1.2.4.1 Active sensors

Active sensors are measuring instruments operating in the EESS which obtain information through the reception of radio waves transmitted from the instrument itself and reflected by the object under investigation. Thus, active sensors are types of radars. Because the reflected signal received by the active sensor depends upon the dielectric properties and roughness of the reflecting surface, the preferred frequency for a given active sensing application depends on the phenomenon being measured. More details on active sensors can be found in Chapter 4 of this Handbook.

1.2.4.2 Passive sensors

Passive sensors are measuring instruments operating in the EESS which obtain information by reception of radio waves of natural origin. Passive sensors measure the noise floor, which is composed of the electromagnetic energy emitted, absorbed, and scattered by the Earth’s surface and the constituents of its atmosphere. Atmospheric gases emit and absorb microwave energy at discrete resonance frequencies described by the laws of physics. Measurements taken near these resonance frequencies can be used to determine the amount of a chemical gas (ozone for one example), the amount of humidity, or water vapour profile, or temperature profile of the atmosphere. Passive sensors can also be used in combination with active sensors for certain types of measurements (e.g., to detect ice in clouds). More details on passive sensors can be found in Chapter 5 of this Handbook.

1.3 Applications of data from EESS missions

While commercial uses of EESS have been growing (for example SPOT, RADARSAT, IKONOS, QuickBird and TerraSAR-X), most usage of the EESS allocations has been for government-sponsored Earth science research and operational weather-related activities.

Earth exploration-satellites enable a diverse set of benefits which include those related to disaster management, the study of natural systems, aspects of humanity and furthering human endeavours.

Disaster management is supported by providing advance information identifying vulnerable areas, forecasting events such as extreme storms and flooding, identifying when and where a disaster has occurred, and monitoring the recovery of an affected area.

The study of natural systems, including biology, geology, hydrology, meteorology, oceanography and climate change, benefit greatly from the truly global observing capability unique to Earth exploration-satellites and the ability of EESS missions to repeat consistent observations over a long period of time.

Aspects of humanity, per se, that benefit from the EESS include archaeology (human history), health (human condition), and population and urban studies (human distribution).

Human endeavours, wherein humanity makes use of the Earth, include raising food (agriculture), mapping the Earth (cartography), planning and implementing communications systems, exploring for energy sources and other natural resources, and planning and optimizing transportation systems.

These societal benefits are available to all humankind as the scientific data and the associated data products are shared with all nations.

The societal benefits of many applications which depend upon data from EESS missions are described in more detail in Chapter 6 of this Handbook.

CHAPTER 2

EARTH EXPLORATION-SATELLITE TELEMETRY, TRACKING, AND COMMAND FUNCTIONS AND TECHNICAL IMPLEMENTATIONS

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2 Introduction

The primary satellite functions discussed below – telemetry, tracking, and command (referred to as TT and C, or TT&C) – are operations functions associated with the satellite bus. The *satellite bus* provides the necessary support functions for the operation of the instruments, which are frequently called the satellite payload. The satellite bus provides power, attitude control (maintaining the desired orientation of the satellite, or satellite pointing), commanding and data handling, health-monitoring (both satellite and payload), station-keeping (i.e., maintaining the desired orbit and correcting for atmospheric drag, orbit precession, etc.), and maintaining the correct thermal environment (e.g., turning on heaters if necessary), amongst other functions.

The transmission of sensor data to earth stations, either directly or indirectly via a data relay satellite (DRS), is carried through the satellite bus and its data handling system. That data path will be referred to as the science data or the EESS data downlink and is discussed in Chapter 3. Typically, the satellite bus links require relatively low bandwidths as they support a data rate of around a Mbit/s and often much less, while the science data (payload) data rates typically are on the order of a hundred Mbit/s.

Discussions of the implementations of Earth exploration-satellite bus telecommunications systems follow the brief introduction of the functions. The allocated bands used for TT&C are given in Table 2-1, although in practice the 2 025-2 110 MHz uplink and 2 200-2 290 MHz downlink bands are the most often used today. Additional wider bands used to downlink science data are described in Chapter 3.

TABLE 2-1

Allocations for EESS and space operations service usable for TT&C
(Space research service and deep space restrictions excluded)

Frequency band	Service	Type of allocation
401-403 MHz	EESS (E-s)	Primary, uplink(1)
401-402 MHz	SOS (s-E)	Primary, downlink(1)
1 427-1 429 MHz	SOS (E-s)	Primary, uplink(1)
2 025-2 110 MHz	EESS (E-s, s-s) SOS (E-s, s-s)	Primary, uplink, direct and via DRS
2 200-2 290 MHz	EESS (s-E, s-s) SOS (s-E, s-s)	Primary, downlink, direct and via DRS
8 025-8 400 MHz	EESS (s-E)	Primary, downlink(2)
13.75-14 GHz	EESS	Secondary
25.5-27 GHz	EESS (s-E, s-s)	Primary, downlink(2) Also via DRS (RR 5.536)
28.5-30.0 GHz	EESS (E-s)	Secondary, uplink(3)
37.5-40.5 GHz	EESS (s-E)	Secondary, downlink
40.0-40.5 GHz	EESS (E-s)	Primary, uplink(3)

(1) Minimal current use of band (2010).

(2) Today (2010) mainly used (or planned to be used) for payload data downlink, although may be used in the future for TT&C.

(3) Minimal current use of band (2010), although these bands may be used in the future.

2.1 Functions

2.1.1 Satellite bus telemetry transmissions

The satellite telemetry subsystem reports the condition of all the satellite systems, including both the bus and its payload, to a designated earth station. These data are sometimes called "engineering data", "housekeeping data", or "health and safety data" and contain parameters such as temperatures, currents, voltages, on/off states, attitude information, etc. If the satellite contains on-board tracking (orbit) information via the radionavigation-satellite service (RNSS, including, for example, the United States' Global Positioning System (GPS) and the Russian GLONASS), that information is also included in the engineering data stream. The TT&C system also gives the status of the reception and execution of commands. Engineering data may be stored on-board the satellite for subsequent transmission or may require immediate (real time) transmission, as is the case for launch and emergency (contingency) operations.

2.1.2 Payload telemetry transmissions

The satellite bus telemetry subsystem is responsible for the transmission to Earth of all engineering data, including that related to the payload. However, payload-related (instrument-related) engineering data may also be embedded in the science data stream as well. Although rarely done, low data rate science data may be included in the satellite bus TT&C downlink data stream in lieu of a separate science data downlink.

2.1.3 Tracking

Tracking provides information necessary to determine the location and velocity of the satellite. Tracking is necessary for evaluating launch and orbit performance, for correcting the satellite's trajectory (determining the precise timing for critical manoeuvres such as thruster firing), and predicting the satellite visibility and antenna pointing angles that are required by the satellite and communicating earth stations or data relay satellites. Without good orbit predictions, earth station satellite contacts cannot be planned.

Tracking data may be determined by an onboard RNSS receiving system and returned to the ground in the engineering data stream. Another approach uses an onboard transponder in conjunction with the command uplink (forward link) and telemetry downlink (i.e., return link). This approach is described in § 2.2.8.2.

2.1.4 Command transmissions

Commands are used to modify the operation of a satellite bus or its payload (i.e., instruments) and to counter operational anomalies. For launch operations, most commands are recorded and delivered by an onboard computer (sometimes called a sequencer). Once the satellite is on orbit, commands are transmitted for immediate execution (i.e., real time execution) or may be stored onboard for later execution. Critical commands are often sent as two stage commands; the first command configures the operation to be taken, and the second command executes the operation. Both commands in a two-stage set must be successfully received for the operation to take place.

2.1.5 Emergency (contingency) communications

Emergency operations occur when there is a failure or malfunction (anomaly) in any system on a satellite. For example, a failure in the attitude determination and control (pointing) system may direct the solar arrays away from the sun, causing the satellite to lose power. In this condition, the satellite can survive only if the attitude control system can be recovered before the on-board batteries are depleted.

All failures require the sending of commands to restore normal operations, even when automatic failure detection systems ("safing" systems) are in place which put the satellite in a safe but non-productive state, often called a "safe mode" of operations. Some system failures can be overcome by switching the satellite to a backup system (a duplicate system normally turned off) providing it is done in time, while other failures may require simply turning off a failed instrument or component (e.g., a failed recorder). More complicated failures may require "safing" the satellite to allow the time for personnel on the ground to analyse the failure and produce corrective commands or new software which circumvents the failure. Most emergency operations are time-critical, so an extremely robust communications system is mandatory.

The allocations near 2 GHz for the EESS (one forward, the other return) provide reliable, weather independent links for Earth exploration satellites. Earth exploration satellites are typically equipped with two antennas operating in the 2 GHz bands oriented at 180° to each other, thereby realizing an overall quasi-omnidirectional pattern. This configuration allows establishing contact between a controlling earth station and the satellite irrespective of the satellite attitude, or orientation. This capability is critical in the launch and early operations phase as well as during any satellite emergency, when the satellite may have lost its desired attitude. Without this feature, no satellite can be launched with a reasonable chance of surviving. This is also the reason why the GSO and non-GSO commercial satellites have TT&C links near 2 GHz where transmission losses are relatively low.

A quasi-omnidirectional antenna cannot be practically implemented on board a satellite at higher frequencies available for EESS operations. Without a quasi-omnidirectional antenna system, some satellite orientations would not allow communications with an earth station, and contact with a distressed satellite might not be possible. In addition to compensating for the increased atmospheric attenuation required at the higher frequencies, any attempt to enlarge the main beam would result in an additional waste of power that is incompatible with the satellite power budget.

Thus one of the major reasons why the 2 GHz band is the workhorse for nearly all the scientific satellites (SRS as well as EESS) is that only frequencies in this range (or lower) are suitable for supporting the critical TT&C functions when spacecraft attitude control is lost.

2.2 Implementation

2.2.1 Propagation considerations

Telecommunication links between earth stations and EESS observation satellites must pass through the Earth's atmosphere where absorption, precipitation, and scattering affect the propagation of radio signals and limit the use of a number of frequency bands. Precipitation, especially rain, causes absorption and scattering of radio waves that can lead to severe signal attenuation. For all rainfall rates, the specific attenuation increases rapidly as a function of frequency up to about 100 GHz, after which the rate of attenuation does not increase appreciably. For countries located in regions of high rain rate, the choice of suitable frequencies is critical if they are to maintain a high quality of performance despite adverse weather conditions.

Sky noise temperature as seen by an earth station antenna is a function of frequency, antenna elevation angle, and atmospheric conditions. Above about 4 GHz, precipitation can result in an increase in sky noise that is several times larger than the receiver noise temperature. The sky noise temperature seen by a spacecraft is determined primarily by celestial bodies such as the moon and the planets that provide the backdrop for most space missions. The blackbody radiation temperatures of the moon and planets range from about 50-700 K (Earth is 290 K). The Sun, with a blackbody radiation temperature of 6 000 K, would greatly increase the system noise temperature and therefore orbits that require a receiving antenna to constantly point at or near the Sun are usually avoided. For many near-Earth missions, the Earth will generally be within the main lobe of a spacecraft or data relay satellite antenna and contribute to the overall noise temperature of the satellite's receiving system. System noise temperatures for typical spacecraft range from 600 to 1 500 K.

Below 100 MHz, spectrum options for Earth exploration-satellite communications are generally not considered because ionospheric effects, cosmic noise and man-made noise mitigate against the use of frequencies in that range.

In the range between 100 MHz and 1 GHz, atmospheric absorption is low and weather has very little effect on signal propagation. Background noise, however, is relatively high and increases as the inverse of the frequency squared. Therefore, the use of low-noise receivers does not provide significant improvement in performance in this range.

In the 1 to 10 GHz frequency range, weather effects are very small, particularly at the lower end of the range, and permit essentially weather independent communications. In this frequency range, both galactic noise and atmospheric noise are low. Therefore, the use of low-noise receivers provides significant improvement in overall system performance in this range.

Above 10 GHz, the propagation of radio signals through the atmosphere is subject to high attenuation due primarily to precipitation and gaseous absorption. Both of these conditions can have a significant effect on communication paths through the atmosphere.

More information on the effects of propagation through the Earth's atmosphere can be found in the ITU-R P-Series of Recommendations on radiowave propagation.

The EESS allocations near 2 GHz are essential for these space missions simply because frequencies in this range are optimal for supporting the TT&C functions from both a technology viewpoint (see § 2.1.5) and considerations of radiowave propagation and background noise effects.

2.2.2 Reliability, bit error rate requirements, and link margins

The command subsystem is of paramount importance to the safety and success of any EESS mission and must function with a high degree of reliability under all adverse transmission conditions, such as unfavourable weather or radio interference. A delay or failure to communicate a command can mean disaster and a costly mission failure.

The need for reliability in telemetry and tracking subsystems is generally less than that needed for command subsystems since missed data or data errors in transmissions usually may be recovered by retransmitting the data without significantly affecting the safety or success of the mission. However, during critical mission events, the reliability of the telemetry and tracking subsystems is as critical as that of the command link.

The reliability requirement for Earth exploration-satellite links during critical mission operations or events has been determined to be 99.99%. This has led the following requirements:

– a weather independent Earth-to-space and space-to-Earth link;
– higher earth station transmitter power levels to compensate for the low gain omnidirectional antennas used by many satellite, especially during launch, orbit injection phases, and contingency (emergency) operations;
– bit error rate (BER) less than 1 x 10^{-5} (less than 1 x 10^{-6} for DRS commands);
– command encoding to ensure sufficient false command rejection due to error bursts, fading or spurious signals;
– sufficient bandwidth to provide all essential information.

Weight restrictions, satellite power limitations and the types of antennas used, all have a significant impact on the capabilities of a satellite TT&C system and therefore system link margins. Earth exploration-satellite link margins are typically between 2 and 6 dB. The preferred methodology for calculating link performance in the Earth exploration-satellite service is provided in Report ITU-R SA.2183.

2.2.3 Data rate and bandwidth requirements

Fundamental among the factors for determining appropriate bandwidths are the data rate requirements of the different satellite communication systems. Telemetry data rates depend on the types of EESS mission, the sophistication of the satellite, the satellite data storage capability and the availability of contact hours between the satellite and the earth stations.

When two or more satellites are required to support the objectives of a single mission, there may be times when more than one satellite will lie within the beamwidth of a common earth station antenna and require simultaneous communications. This operational requirement necessitates an earth station bandwidth wide enough to accommodate several satellite signals and that the satellite operating frequencies and/or modulation schemes avoid interfering with each other.

An alternative approach to TT&C is to utilize a DRS system. DRS feeder links are a composite link composed by multiplexing the links of the client low-Earth orbiting (LEO) satellites along with the DRS telemetry and ranging channels and pilot signal.

Detailed discussions on Earth exploration-satellite mission bandwidth requirements and hypothetical reference system can be found in Recommendations ITU-R SA.363, ITU-R SA.364, ITU-R SA.1019, ITU-R SA.1020 and ITU-R SA.1024.

2.2.4 Multiplexing

Both time-division multiplexing (TDM) and frequency-division multiplexing (FDM) are employed by EESS systems. TDM is used by EESS missions to place digitized packets of data from different systems onboard a satellite bus into a single engineering data stream, such as used on Consultative Committee for Space Data Systems (CCSDS) telemetry packets. This approach facilitates the transmission of data in a standardized and automated manner.

For DRS operations, TDM is used to relay commands to multiple satellites and to provide discrete channels between the ground stations and the satellites.

DRS operations also use FDM. The command data are conditioned and modulo-2 added asynchronously to the command channel pseudo-noise (PN) code (most LEO satellites use the command channel PN code for signal acquisition). This code plus data is then used to bi-phase modulate the command channel intermediate frequency (IF) carrier. If ranging is required, a long PN code bi-phase modulates the ranging channel IF carrier. The ranging channel is then combined to the command channel in radio frequency (RF) phase quadrature. The IF output of the quadri-phase modulator is then equalized, frequency translated, amplified and switched to the RF combiner assembly where, a composite forward link signal is passively formed with signals for other LEO satellites, the DRS forward command channel, and pilot tone information. This composite link is finally routed to the selected transmit antenna for transmission to the DRS. At the DRS, the received signal is translated to an IF, amplified, filtered and de-multiplexed. Signals for transmission to different LEO satellites are translated to the appropriate frequency, amplified, and transmitted by the appropriate antenna to the corresponding LEO satellite. The DRS forward command channel and pilot tone are frequency translated and sent to the DRS space operation subsystem.

Return operations are similar to the forward link operations except that the signal flow is reversed. LEO satellite signals are received by the DRS antenna, amplified, down-converted to an IF and sent to the return processor assembly where they are multiplexed with other LEO satellite received signals, DRS telemetry and the return link pilot tone. This composite return link signal is up-converted, amplified, and transmitted to Earth by the DRS feeder link antenna. Signals from LEO satellites with very high data rate return channels are not multiplexed with other received signals. These signals are routed to a separate dedicated return processor, where they are up-converted and amplified to form a dedicated return link signal for transmission to the receiving earth station.

2.2.5 Error correction coding techniques

Error correction coding techniques are frequently used to improve the bit error rate (BER) of Earth exploration-satellite communication links. Because these techniques introduce redundancy into the message before transmission, they require an increase in the signal bandwidth. Since this type of coding allows for the correction of transmission errors, the signal transmit power can be reduced accordingly. For power-limited satellites, there are advantages to using a modest amount of error correction coding to ensure greater system margins.

Error correction codes may be used to correct single bit errors or error bursts. A trade-off must be made between error-correcting efficiency for a particular error effect and the expense and/or time-delay required for their physical implementation. The basic error correction code used by the EESS is a rate 1/2, constraint-length 7, transparent convolution code well suited for channels with predominantly Gaussian noise. Convolution encoding at the satellite and sequential decoding at the ground terminal enhance the overall system performance independent of the modulation technique. Reed-Solomon (RS) coding is usually added to reduce error probability rather than reduce E_b/N_0. The RS code is a powerful burst error correcting code that has an extremely low undetected error rate. This code may be used alone, and as such provides an excellent forward correction in a burst-noise channel, or the code may be concatenated with convolution codes, with the convolution code as the inner code and the RS code the outer code. This configuration may also be used with interleaving. The interleaver placed between the RS (outer) code and the convolution (inner) code breaks up any bursts that appear in the convolution decoded output.

A pseudo-random noise (PRN or PN) code system is an integrated system that can provide simultaneous functions such as data transfer and ranging in a single integrated waveform that has applications in many missions. A PN code system provides immunity to multi-path interference signals, even at very low altitudes encountered during the initial launch phase of a satellite's mission. Narrow-band interference sources are rejected by the PN code tracking receiver, and broadband interference and noise is rejected when a narrow-band signal is demodulated by the phase tracking receiver. Another benefit of PN code systems is that the PN modulation spreads the transmitter power over a larger bandwidth keeping the power flux-density at the surface of the Earth at or below levels specified in the Radio Regulations (RR).

2.2.6 Pseudo-random noise coding techniques

PN code systems are used to support DRS communications due to their ability to permit positive identification and multiplexing of a large number of satellites through a common frequency band, or channel. The coordination of PN code libraries permits interoperability between agencies and avoids mutual interference. Two types of PN codes are used in determining code libraries, gold codes (short codes) and maximal length codes (long codes). Gold codes are a class of codes that have low cross-correlation properties. The codes are short to permit rapid signal acquisition. Gold codes are used in the forward link command channel and by satellite transmissions requiring a non-coherent return link. Maximal length codes are considerably longer than gold codes and are utilized to provide good range ambiguity resolution.

Synchronous forward and return PN codes provide accurate range measurements (coherent transponding) by comparing the relative phases of the transmitted and received PN code generators at the ground terminal. The system can provide Doppler compensation for DRS links from the earth station to satellite and back to the earth station. This ensures that any Doppler contribution due to the motion of the DRS will not degrade or bias the overall system's performance.

2.2.7 Modulation techniques

Analogue modulation techniques are rarely employed by Earth exploration-satellite missions as digital phase modulation (PM) techniques are the predominant systems in use. An appropriate modulation index results in a residual carrier that is used for tracking the received signal. Use of this technique keeps the data power substantially outside the receiver carrier tracking loop bandwidth, maintains simplicity in the design of the satellite, and provides reliability and optimum performance of the telecommunication link.

Direct-to-Earth and DRS systems use different variants of phase modulation. Direct-to-Earth missions generally use binary phase shift keying (BPSK) for a single data channel or quadrature phase shift keying (QPSK) for two independent channels. DRS systems are also available for direct-to-Earth missions. DRS systems use pseudo-random noise spreading in addition to unbalanced QPSK.

2.2.8 Acquisition

Acquisition is the establishment of a communication link between a satellite and an earth station or DRS that permits the uninterrupted flow of data. Acquisition is a key element in the communication sequence of events.

2.2.8.1 Non-coherent acquisition

Operations may be initiated by the earth station sending a command to the satellite to start its transmitter, or by the satellite, operating on a stored command, transmitting in the direction of a receiving earth station with a power compatible with its data rate. The earth station antenna, in this case, follows the satellite across the sky using the predicted satellite orbit to calculate its antenna pointing. A priori knowledge of the satellite local oscillator frequency permits the earth station (or DRS) to search, acquire and lock onto the incoming signal. One-way Doppler measurement, if needed, is based on received frequency and tolerance of the satellite local oscillator.

If an auto-track system is in place at the earth station, the satellite carries a beacon transmitter which provides a signal used to guide the earth station's antenna. In this case, the earth station only needs a time, azimuth, and beacon frequency to locate the satellite when it appears on the horizon; no further orbit predictions are needed, although the length of the contact (pass) is needed to plan operations. Once the antenna locks onto the beacon signal, the earth station sends a command and communications commence; the antenna automatically follows the satellite until it disappears over the other horizon.

2.2.8.2 Coherent acquisition and DRS

Some Earth exploration-satellite communications require coherent operations to provide satellite tracking data. An on-board transponder is used for that purpose. For these operations, a forward link from an earth station to a satellite must first be acquired prior to return link acquisition and subsequent data flow from between the satellite and the earth station. This action allows the satellite return carrier frequency and PN (range) code to be coherently related and locked to the received forward link signal from the earth station. DRS operations have the additional complexity of having to route the forward and return link signals through the DRS.

The duration of time for an acquisition sequence is generally short, of the order of 5-10 seconds. However, during interference events, which can cause loss of signal or unlocking of the signal carrier from the carrier tracking loop, seconds may elapse before reacquisition of the signal is established.

2.2.8.3 Turnaround ratios

The satellite transmit frequency is sometimes coherently related to the carrier frequency it receives from an earth station or from a DRS satellite. This frequency relationship is based on a specific multiple known as the "turnaround ratio" that is applied at the satellite.

$$\text{Frequency transmitted} = \text{Frequency received} \times \text{Turnaround ratio}$$

Turnaround ratios depend on the frequency band used. For the EESS, the 2 GHz band can be used for direct earth station-to-satellite communications and the commonly used turnaround ratio is equal to 240/221.

2.2.9 Tracking techniques

Radar tracking is used during launch operations. Rather than rely on weak echoes, many satellites carry beacons or transponders for tracking operations. Atmospheric attenuation usually limits radar tracking operations to frequencies below 6 GHz.

Coherent and non-coherent range and range-rate tracking provides tracking accuracy which surpasses that available from ground-based radar networks. Range or distance is determined by measuring the round trip time of a radio signal from an earth station to a satellite and back to the earth station. Range-rate or velocity is determined by measuring the Doppler shift in frequency of the signal. Ranging and range-rate are of critical concern for EESS satellites not equipped with an RNSS receiver, especially when precise orbit determination accuracy is needed such as for altimeter payloads.

On-board tracking may be accomplished using one of the RNSS systems. Using this approach, an RNSS receiver is carried onboard the satellite, and the position and velocity data produced by that device are included in the engineering data stream returned to the earth stations. This approach has the advantage of not requiring any specialized ground equipment or any passes supported by such specialized equipment. Furthermore, it can produce and record position data continuously, even when out of contact with a ground station. This capability is particularly important when a satellite manoeuvre, accomplished by firing thrusters, is performed when the satellite is unobservable by any earth station and triggered by a stored command.

Tracking is used to produce orbit predictions and ephemerides, which are then used to schedule future contacts, or passes, with the satellites, regardless of whether the contact is with an earth station or DRS satellite. Tracking is critically important to EESS missions for providing the location (sub-satellite point on the Earth's surface) of the Earth exploration-satellites. The location of the satellite as a function of time is called the satellite's ephemeris. The orbit predictions are an extrapolation based on the most recent tracking data, while the "final" or "definitive" ephemeris is usually an after-the-fact ephemeris based on the best fit to all available tracking data. The final satellite ephemeris, coupled with satellite attitude and instrument pointing information, are necessary to identify the location on the surface of the Earth being observed or the path through the atmosphere being observed.

2.2.9.1 Non-coherent tracking

In non-coherent earth station/satellite operations, the satellite local oscillator generates and transmits a reference carrier frequency that is known to the receiving earth station. A Doppler extractor at the earth station compares the received frequency against a locally generated reference frequency to determine Doppler shifts.

Alternately, satellites that carry RNSS receivers produce their own tracking data onboard, and these data are embedded in the engineering data stream. The RNSS tracking (i.e., position and velocity) data may be embedded in the science data stream as well. The raw RNSS-derived spacecraft ephemeris is usually adequate for real time applications.

2.2.9.2 Coherent tracking

Coherent operations provide for two-way range and Doppler measurements. The earth station transmits the carrier frequency modulated by a specific ranging code. The satellite receives and phase locks to the received frequency, and generates a transmit carrier frequency coherent with the received signal using a device called a transponder. This coherent frequency is based on the turn-around-ratio defined by the space administration or network (see § 2.2.8.3). A ranging code, synchronous with the received ranging code, is generated by the satellite and used to modulate the transmit frequency. The earth station receives and phase locks the incoming signal and compares it against the reference frequency initially radiated by the earth station to determine the Doppler measurements. Range measurements are determined at the earth station by measuring the time elapsed between the moment of transmission of elements in the forward range code, and the moment of reception of the same elements back at the earth station. This technique must be used when tracking depends upon communicating through a DRS.

Tone ranging involves the transmission of two or more frequencies to create the ranging function. Major and minor tones are in the kHz frequency range. Side-tones are used for ambiguity resolution.

CHAPTER 3

EARTH EXPLORATION-SATELLITE SERVICE SCIENCE DATA DOWNLINK FUNCTIONS AND TECHNICAL IMPLEMENTATION

Page

3 Introduction

Factors that affect the suitability of specific frequencies for Earth exploration-satellite data downlink include mission requirements, data rate requirements, equipment availability/cost and link performance. But the first and essential factor is the availability of frequency allocations by the ITU and within these allocations a favourable operating environment with minimum interference.

3.1 EESS data downlink allocations

Preferred frequency bands for the Earth exploration-satellite downlink can be found in the Recommendations ITU-R SA.1024 and ITU-R SA.1019.

The bands allocated for EESS downlinks are summarized in Table 3-1. MetSat downlink bands are discussed in the Handbook produced jointly by the ITU and the World Meteorological Organization titled – Use of Radio Spectrum for Meteorology: Weather, Water, and Climate Monitoring and Prediction, Edition 2008.

TABLE 3-1

Allocations for EESS downlink usage

Frequency band	Service	Type of allocation
460-470 MHz	EESS (s-E)	secondary (see RR. No. 5.289)
1 690-1 710 MHz	EESS (s-E)	secondary (see RR. No. 5.289)
2 200-2 290 MHz	EESS (s-E)	primary, direct and via DRS
8 025-8 400 MHz	EESS (s-E)	primary downlink
25.5-27 GHz	EESS (s-E)	primary, direct and via DRS
37.5-40 GHz	EESS (s-E)	secondary

As indicated in Recommendation ITU-R SA.1024, three primary bands are available for direct data downlink: S-band (2 200-2 290 MHz), X-band (8 025-8 400 MHz) and Ka-band (25.5-27 GHz). Further bands are available for MetSat usage and are not included here.

The S-band downlink is recommended only for low data rate science (payload) data. In this band, the EESS payload data are interleaved with the TT&C data. For this band allocation, the driving requirements are the ones given by the TT&C function. This type of link is discussed in Chapter 2, while this chapter focuses on the X-band (high data rates, ~ 100 Mbit/s) and Ka-band (very high data rates, >150 Mbit/s).

3.2 Mission considerations

The vast majority of EESS missions operate in a low-Earth orbit (LEO) with a high, nearly polar, inclination. These orbits exploit the Earth’s rotation underneath the satellite's orbital plane as a means to observe the whole surface of the globe, although a number of orbits are needed to provide complete coverage. The typical orbital heights range between 700 and 800 km, with some satellites deployed as low as 400 km or as high as 1 000 km. Several factors related to the observation requirements constrain the choice of the orbit height, its inclination and the ascending/descending equator crossing time.

The science data are typically stored on board a satellite during data acquisition by its instruments and downlinked to associated earth stations when the satellite is in line-of-sight of them. These occurrences are called “passes” or “contacts”, and the operations planned for each pass over an earth station depend on the timing in the satellite’s orbit, the amount of data stored onboard that must be downlinked, the length of the pass (for an orbit of 700 km, the longest pass is around 11 minutes), the available data rates (typically ~ 100 Mbit/s), and considerations relating to the next available pass, such as commands that must be uplinked, onboard storage that must be made available, any constraint imposed by a satellite anomaly or failure, etc.

EESS ground stations receiving science data from polar-orbiting satellites are often located at high latitudes to take advantage of a geometry that gives more than twice the number of passes per earth station per day when compared to a low-latitude, or equatorial, earth station. Mid-latitude or low-latitude earth stations typically see only 5 passes per day, with 2 or 3 of these passes being quite short. This high-latitude system architecture allows reducing both satellite storage requirements and the number of earth stations.

Other less used options for transmitting the science data to the ground are:

– Directly broadcasting the data immediately after acquisition.

– Transmissions via a data relay satellite (DRS) system.

The direct broadcasting option (also called direct readout) is typically used only for relatively low data rate science data (typically 10-20 Mbit/s) that are of general interest and do not require complex processing by the receiving station. The data downlinked via direct broadcast is raw sensor data; hence the need for processing by the receiving station before the data can be used. These ground stations typically deploy small antennae (typically 3 m in diameter) and are located in the same geographical area where the satellite measurements take place. The stations are receive-only and cannot command the satellite; hence, the direct broadcast system on an Earth exploration-satellite is turned off only when necessary. These stations depend on obtaining orbit predictions to schedule their passes and to steer their antennas. The science data are received in real time (immediately after being taken by the instrument) and are usually quickly processed. One example is the wildfire monitoring stations which observe large, sparsely populated areas prone to, or vulnerable to, wildfire outbreaks. These monitoring stations are used to identify wildfire outbreaks, to alert people endangered by the wildfire, and to guide fire-fighters as they work to control the fires. Immediate receipt and timely processing of the science data are clearly critical in this application.

The data relay satellite (DRS) system downlink may be used in lieu of high-latitude ground stations to increase the overall satellite downlink capability, or to reduce the data latency (the time between an observation by a sensor and the receipt of the data on the ground). However, this approach represents a non-negligible additional mission cost and the attendant risk of a steerable (moveable) antenna failure.

The link reliability requirements for data downlink transmissions vary depending on the mission objectives (e.g., maximum data latency), data integrity, and the capability of the satellite to retransmit the data on a later pass.

The performance requirements for EESS data downlinks are contained in Recommendation ITU-R SA.1025. The methodology to be used in determining performance objectives is given in Recommendation ITU-R SA.1021.

3.3 Data rate requirements

Higher frequency allocations generally provide for wider bandwidth channels. Wider bandwidth channels provide the ability to support higher data rate requirements and the use of more complex coding schemes which reduce error rates and lower susceptibility to interference. The main reasons for the higher data rate requirements of most of the new EESS missions are the increased complexity (more data points per instrument) and precision (more bits per data point) of the EESS payloads. Factors affecting the data rate requirements are:

– Spatial resolution: requirements can be less than 1 metre on the Earth's surface;

– Swath width: typical requirements range from greater than 1 000 km to a few tens of km (for very high spatial resolution images);

– Radiometric resolution: requirements continuously increasing due to improving instrument technology;

– Spectral resolution: this factor applies mainly to optical measurements and can go up to hundreds of spectral measurements at different wavelengths for hyper-spectral payloads.

The typical range for medium-rate to high-rate EESS payload data is from a few tens of Mbit/s to 0.5 Gbit/s, although the trend is for the upper end of the range to increase further.

Other considerations related to the availability of a backup downlink channel at a different frequency lead to the doubling of the required bandwidth.

3.4 Equipment considerations

Direct data downlinks in X-band (~8 GHz) typically use isoflux antennas (i.e., antennas providing a power flux density (PFD) on the ground roughly equal at any point in the antenna's footprint on the ground). This relatively constant PFD is achieved by enhancing the gain towards the more distant areas of the footprint (higher spacecraft off-nadir angle) with respect to the gain in the nadir direction (directly beneath the satellite), which is less than unity. The overall result is a signal that appears to be constant to within a few dB while the satellite moves from 5° above the horizon to directly overhead and back to 5° above the horizon.

The isoflux approach simplifies the design of the satellite antenna as no pointing is needed, and data can be received simultaneously by any user in line-of-sight of the satellite. This approach is particularly useful for direct broadcasting operations. For downlinking (dumping) the onboard stored data (at typically ~ 100 Mbit/s), a 10 m diameter receiving antenna is usually required, while the lower data rate direct broadcast systems (at typically ~ 15 Mbit/s) require only a 3 m diameter receiving antenna.

At higher frequencies (~ 26 GHz), the higher and more variable atmospheric attenuation makes an isoflux antenna design demand more power from the satellite to compensate for the increased losses. Therefore, more directive antenna patterns are needed at Ka-band and higher frequencies to minimize the transmitter power required. While directive antenna patterns allow important power savings, they:

– Increase the satellite design complexity due to the need for a steerable onboard antenna. Phased array antennas are not yet commonly used for this purpose. The alternative mechanically pointed parabolic antennas are inherently less reliable than a fixed isoflux antenna, thus directly impacting the overall satellite reliability.
– Present a variable link budget at different angles during the satellite pass over the station due to the changing distance from the earth station to the satellite. Among the techniques to compensate for this effect are increasing transmitter power at longer ranges (larger off-nadir angles) and variable coding and modulation (VCM) schemes, which produce variable data rates (lower data rates at longer ranges with the highest data rate when the satellite is directly overhead) during a satellite pass.

The availability of space qualified hardware is a limiting factor to the use of higher frequencies. Currently, the most mature EESS high rate data downlink hardware has been developed for the X-band allocation. For this reason the EESS X-band allocation, despite its bandwidth limitation of 375 MHz, is widely used by Earth exploration-satellites.

Time-division multiplexing is used by EESS missions to place digitized packets of data from different instruments onboard a satellite into a single data stream, such as used on Consultative Committee for Space Data Systems (CCSDS) telemetry packets. This approach facilitates the transmission of source data in a standardized and automated manner.

Data compression is also applied on-board to reduce the downlink rate requirements and consequently the bandwidth requirements.

Error correcting codes and pseudo-random noise coding (described in § 2.2.5) are also implemented in the science data downlinks to reduce the required transmitter power and to increase the robustness of the communication link. These techniques are applied after the raw science data has been pre-processed or compressed. However, there is a systems-level trade-off to be made between the bandwidth required for the error-correcting schemes (more is usually better), the transmitter power required (less is better), and the available allocated downlink bandwidth (fixed, and must be shared with other missions). Achieving an acceptable bit-error-rate is the overarching goal.

Modulation and coding technology is evolving towards more spectrum-efficient schemes that allow more data to be transmitted in the available X-band bandwidth, but this has to be balanced against the risk of reducing the robustness of the link and consequently increasing its sensitivity to RF interference. The typical ratio achieved by satellites currently in operation is 1 bit/s/Hz, but a number of new satellites are expected to achieve a bandwidth efficiency of up to 2.25 bit/s/Hz.

Other advances in technologies are aimed at reducing the strength of unwanted sidebands of the transmissions. Such techniques include using advanced filters on the transmitted signal and using modulations such as offset-QPSK and Gaussian-shaped QPSK.

3.5 Effects of interference on EESS data downlink

A typical EESS terrestrial receiver contains synchronized phase-lock loops designed to lock and track the received signal. The presence of a strong interfering signal may cause these receivers to lose lock with the desired signal resulting in a break in communications. Interference can be momentary, caused by the interfering signal sweeping across the loop bandwidth, or it may last for minutes. In such a case, a recovery procedure must be initiated to reacquire and regain lock with the desired signal. The duration of the reacquisition sequence may be longer than the duration of the interference itself. The result of such harmful interference is the reduction, interruption, or irretrievable loss of the data transmitted to the ground by the satellite during its pass over the earth station.

As explained above, the geometry of a LEO polar orbit (for example, with an altitude of 700 km) is such that even at high latitudes, for each orbit of about 100 minutes, the duration of a pass for an earth station ranges between less than 5 minutes to 11-12 minutes, with not all orbits visible from a given earth station. Unfortunately, interference lasting only minutes or less can result in the loss of much of the data transmitted during that pass. In extreme cases, the whole data set could be lost.

Interference to the earth station receiving the EESS data downlink may originate from:

– emissions from other satellites (EESS or non-EESS) sharing the same frequencies;
– emissions from systems of terrestrial services sharing the same frequencies and operating in an area close to the EESS earth station; or
– unwanted emissions from systems of other satellite or terrestrial services operating in adjacent bands.

3.5.1 Emissions from other satellites sharing the same frequencies

An Earth exploration-satellite may at times be subject to interference from other satellites since all Earth exploration-satellites share the same allocated frequency bands as given in the Radio Regulations, and these bands are also shared with other satellite services. An earth station may receive interference from another satellite located within the beamwidth of its receiving antenna, or from satellites which produce interference due to their proximity to the earth station or to their high transmitter power. The orbital configuration of the satellites (proximity to each other) and the power and spectrum of the transmitted signals determine the timing and level of interference.

Recommendation ITU-R SA.1810 provides design guidelines and interference mitigation techniques that are meant to optimize the use of spectrum in the 8 025-8 400 MHz band and to reduce the risk of interference between EESS systems. Similarly, Recommendation ITU-R SA.1862 provides guidelines that are meant to optimize the use of spectrum in the 25.5-27 GHz band and to reduce the risk of interference between satellite systems using this band.

3.5.2 Emissions from systems of terrestrial services

For satellites operating in the EESS, the location and concentration of terrestrial emitters with respect to the receiving EESS earth station are important factors in interference considerations and may have a very pronounced effect on the sharing environment.

Mobile terrestrial stations pose a difficult problem, where the unknown density and location of the stations do not allow any form of coordination. For this reason similar conclusions can be drawn in the bands 8 025-8 400 MHz and 25.5-27 GHz with respect to the conclusions in Recommendation ITU-R SA.1154 for the band 2 200-2 290 MHz. In this Recommendation, the deployment of high density or conventional mobile systems in the band 2 200-2 290 MHz is indicated as incompatible with the use of EESS space-to-Earth systems. For the case of fixed terrestrial systems, coordination mechanisms are applied (see § 3.6.2).

3.5.3 Unwanted emissions from systems operating in adjacent bands

A third possible interference source is unwanted emissions from systems operating in adjacent or nearby bands. The potential for harmful interference resulting from unwanted emissions is an issue that affects all services. Spurious emission due to signal harmonics generated by transmitter intermodulation effects are a particular concern for spaceborne emitters because large amounts of spectrum can be affected and transmitter adjustments or modifications are normally limited or impossible after the launch of a satellite.

No specific regulatory limits exist on unwanted emissions in the bands 8 025-8 400 MHz and 25.5-27 GHz, beside the generic ones contained in Appendix 3 of the Radio Regulations which are applicable to all emissions in any frequency band.

As for unwanted emissions affecting systems of other services from the EESS (space-to-Earth) transmissions, it is to be noted that specific emission masks on the Earth exploration-satellite emissions have been voluntarily adopted by all the major space agencies under the framework of the Space Frequency Coordination Group (SFCG). A particular problem is posed by the deep space downlink band located at 8 400-8 450 MHz, directly adjacent to the 8 025-8 400 MHz EESS downlink band. In addition to the need to return as much data as possible in the 8 025-8 400 MHz EESS allocated band, the extreme sensitivity of the deep space ground stations to out-of-band interference requires special care be taken to meet acceptable interference PFD levels. In the worst case, an EESS mission may have to coordinate with the deep space ground stations and to avoid transmitting from orbit when close to where a deep space antenna is pointing.

3.6 Protection from interference

The protection criteria for EESS systems operating in the bands used for data downlink (8 025-8 400 MHz and 25.5-27 GHz) are given in Recommendation ITU-R SA.1026. This Recommendation identifies the global interference levels and the percentage of time these levels can be exceeded for long-term and short-term protection of EESS systems.

3.6.1 EESS protection criteria

Based on the interference criteria, the anticipated spatial deployment of interfering stations, and the associated temporal characteristics of interfering signals, Recommendation ITU-R SA.1027 gives the applicable sharing criteria for the long-term interference (20% of the time) and short term interference (<1% of the time).

Individual receiving stations need to be protected from interference by stations of terrestrial systems and by satellite downlinks of other EESS systems.

The analysis relevant to terrestrial systems is begun by defining a coordination area using Appendix 7 of the Radio Regulations and is followed by the verification of compatibility with each known nearby terrestrial system using the interference criteria. A minimum EESS earth station antenna elevation angle of 5° is used for this analysis; that is, the satellite must be at least 5° above the horizon before the signal is acquired and a contact begins. This elevation angle is consistent with operational experience.

Due to the clustering of many EESS earth stations at high latitudes, the widespread use of isoflux antennas, and the need for many EESS missions to use large portions, if not all, of the same allocated bands, coordination among the various EESS missions critical. In order to minimize the interference risk, Recommendations have been developed in ITU-R for the 8 025-8 400 MHz band (Recommendation ITU-R SA.1810) and for the 25.5-27 GHz band (Recommendation ITU-R SA.1862). These Recommendations give mission design guidelines that reduce the interference risk and allow for a more effective and efficient use of these frequency bands.

3.6.2 Sharing and coordination

Frequency sharing between the EESS and other services is necessary when bands are co-allocated to multiple services. Interference between systems can be mitigated based on sharing conditions established as the result of analysis completed on behalf of both services.

The sharing criteria for the EESS bands used for data downlinks (8 025-8 400 MHz and 25.5-27 GHz) are given in Recommendation ITU-R SA.1027. This Recommendation provides an apportionment of the interference thresholds given in Recommendation ITU-R SA.1026 between space and terrestrial interferers.

Article 21 and Appendix 7 of the Radio Regulation (RR) form the basis for coordinating between EESS earth stations and terrestrial systems. RR Article 21 addresses terrestrial and space services sharing frequency bands above 1 GHz. RR Appendix 7 provides the method for the determination of the coordination area around an earth station in frequency bands between 1 GHz and 40 GHz shared between space and terrestrial radiocommunication services. It therefore applies to the bands 8025-8400 MHz and 25.5-27 GHz.

The protection of the terrestrial services from EESS space-to-Earth transmissions is ensured by applying the relevant Earth surface power flux density limits given in RR Article 21.

CHAPTER 4

SPACEBORNE ACTIVE MICROWAVE SENSORS OPERATING IN THE EARTH EXPLORATION-SATELLITE SERVICE (ACTIVE)

Page

4 Introduction

The purpose of this section is to describe the radio spectrum frequency needs of the spaceborne active sensors in the EESS (active). The intent is to present the unique types of sensors and their characteristics which determine their individual frequency needs; to present the preferred frequencies and bandwidths; to present performance and interference criteria necessary for compatibility studies with other services in the frequency bands of interest; and to present sharing considerations.

4.1 Active sensor types

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

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

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

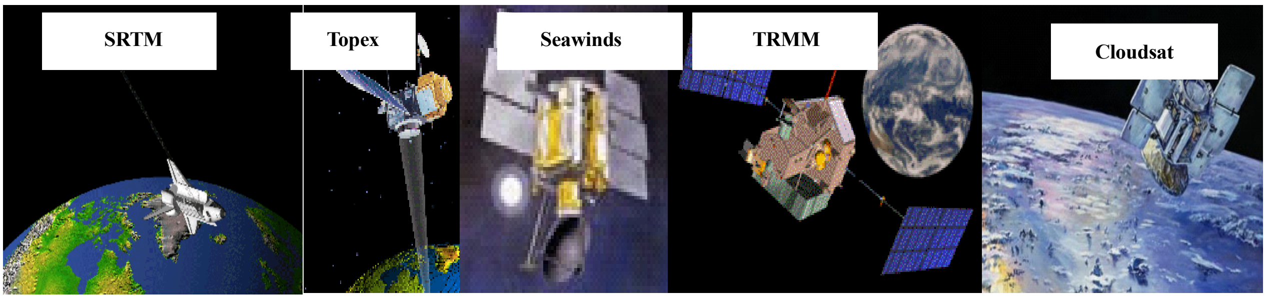
Type 3: *Scatterometers* – Sensors pointing at various look angles relative to the sides of the nadir track, using the measurement of the return echo power variation with aspect angle to determine the brightness of the radar echo return of land or to determine the wind direction and speed on the Earth's ocean surface.

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

Type 5: *Cloud profile radars* – Sensors looking at nadir which measure the radar echo return from clouds in order to determine the cloud reflectivity profile over the Earth's surface. Examples of the five types of spaceborne active sensors are shown below in Fig. 4-1:

FIGURE 4-1

Examples of five types of spaceborne active sensors



The characteristics of the five key types of active spaceborne sensors are summarized in Table 4-1.

TABLE 4-1

Active spaceborne sensor characteristics

Characteristic	Sensor types				
	SAR	**Altimeter**	**Scatterometer**	**Precipitation radars**	**Cloud profile radars**
Viewing geometry	Side-looking at 10°-55° off nadir	Nadir-looking	– Three/six fan beams in azimuth – One or more conically scanning beams	Nadir-looking	Nadir-looking

TABLE 4-1 (*end*)

Characteristic	Sensor types				
	SAR	**Altimeter**	**Scatterometer**	**Precipitation radars**	**Cloud profile radars**
Footprint/-dynamics	– Fixed to one side – ScanSAR	Fixed at nadir	– Fixed in azimuth – Scanning	Scanning across nadir track	Fixed at nadir
Antenna beam	Fan beam	Pencil beam	– Fan beams – Pencil beams	Pencil beam	Pencil beam
Radiated peak power (W)	1500-8000	20	100-5000	600	1000-1500
Waveform	Linear FM pulses	Linear FM pulses	Interrupted CW or short pulses (ocean) or linear FM pulses (land)	Short pulses	Short pulses
Bandwidth	20-300 MHz	320 MHz	5-80 kHz (ocean) or 1-4 MHz (land)	14 MHz	300 kHz
Duty factor (%)	1-5	46	31 (ocean) or 10 (land)	0.9	1-14
Service area	Land/coastal/ocean	Ocean/ice	Ocean/ice/land	Land/ocean	Land/ocean

4.1.1 Synthetic aperture radars

SARs provide radar images of the Earth's surface or topographic maps from interferometric returns. The choice of RF centre frequency depends on the Earth's surface interaction with the electromagnetic field. The RF bandwidth affects the resolution of the image pixels. In Fig. 4-2 a), the chirp pulse is shown, and the corresponding RF bandwidth is shown below. The range resolution is equal to:

$$c/(2\ \mathrm{BW}\sin\theta)$$

where:

- c: the velocity of light
- BW: the RF bandwidth
- θ: the incidence angle.

To obtain 1-metre range resolution at 30° incidence angle, for instance, the RF bandwidth should be 300 MHz. Many SARs illuminate the swath off to one side of the velocity vector as shown in Fig. 4-2 b).

Equation (4-1) gives the expression for calculation of the SAR return power level of the Earth's surface.

$$P_r = \frac{P_t G^2\ \delta_r \tau_p f_{PRF}\ \sigma_0}{2 v l_s}\left(\frac{\lambda}{4\pi R}\right)^3 \quad \mathrm{W} \qquad (4\text{-}1)$$

where:

- P_r: SAR return power level of the Earth's surface (W)
- P_t: radar transmit power (W)
- G: antenna gain
- δ_r: range resolution (m)
- τ_p: pulse width (s)

f_{PRF}: pulse repetition frequency (Hz)

σ_0: backscatter coefficient

λ: wavelength (m)

v: platform velocity (m/s)

l_s: system loss

R: range (m).

Any interference sources within the illuminated swath area will be returned to the SAR receiver and the interference power I will be added to the SAR return power level of the Earth's surface, P_r.

For an interferometric SAR (InSAR), the difference in phase of two SAR returns of the same area with a slightly different aspect is used to determine the topographic height of the pixels. Equation (4-2) gives the absolute height accuracy σ_{abs} as the accuracy of surface height estimates with phase noise for two observation locations with a baseline at an angle from the horizon:

$$\sigma_{abs} = \frac{\sigma_\varphi}{\sqrt{N_s}} \frac{\lambda R_0 \sin\theta_i}{2\pi B_L \cos(\theta_L - \alpha)} \quad \text{m} \tag{4-2}$$

where:

σ_φ: phase noise (radians)

λ: wavelength (m)

R_0: slant range to the pixels

θ_i: incidence angle (degrees)

N_S: number of samples

B_L: baseline length (m)

θ_L: look angle (degrees)

α: baseline angle from horizon (degrees)

For a differential interferometric SAR, the differential phase between two sets of SAR returns of the same area with a slightly different aspect is used to determine the differential topography. Equation (4-3) gives the differential height accuracy σ_{diff}:

$$\sigma_{diff} = \frac{\lambda \sigma_\phi}{4\pi\sqrt{N_s}} \tag{4-3}$$

where:

λ: wavelength (m)

σ_φ: phase noise (radians)

N_S: number of samples

The allowable image pixel quality degradation determines the allowable interference level. For SARs, the allowable image pixel quality degradation is a 10% degradation of the standard deviation of the pixel power. This yields an interference-to-noise power ratio of –6 dB, or $I/N = -6$ dB.

Some examples of SARs in three separate frequency bands are:

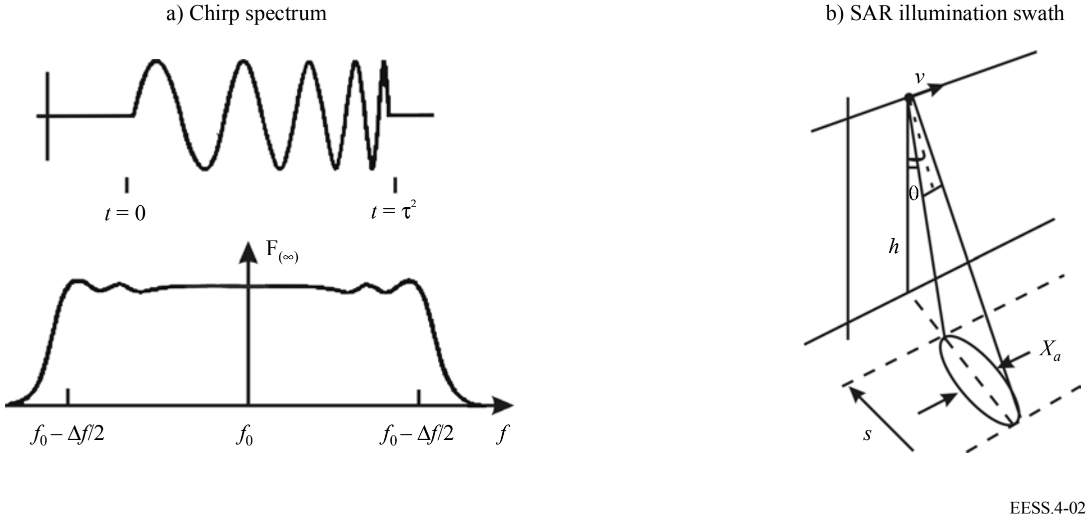
– the PALSAR, JERS-1 and DESDynI in the 1215-1300 MHz band;

– the RADARSAT, ASAR and ERS in the 5250-5350 MHz band;

– the SRTM X-SAR in the 9500-9800 MHz band.

FIGURE 4-2

Chirp spectrum and SAR illumination swath



4.1.1.1 1.25 GHz SAR

The 1.25 GHz SARs are active microwave sensors using the L-band frequency band 1 215-1 300 MHz to achieve cloud-free and day and night land observation. The SARs may have several modes, including fine resolution mapping modes, medium resolution mapping modes, and scanSAR modes. Typical characteristics of 1.25 GHz SARs are shown in Table 4-2 with ranges of parameter values including characteristics of PALSAR, JERS-1 and DESDynI.

TABLE 4-2

Typical characteristics of 1.25 GHz, 5.3 GHz and 9.6 GHz SARs

Parameter	1.25 GHz SAR	5.3 GHz SAR	9.6 GHz SAR
Antenna type	Parabolic offset fed to active phased array	Passive waveguide to active phased array	Planar slotted waveguide array
Frequency band (MHz)	1215-1300	5300	9600
Peak power (W)	1100-3200	1500-4000	1400
Antenna peak gain (dBi)	33-45	40-44	44.5
Pulsed bandwidth (MHz)	15-80	11-30	10-20
Off-nadir angle (degrees)	10-55	20-46	20-55
Altitude (km)	568-757 (at Equator)	785-800	225
Inclination (degrees)	98	98-98.574	28
Type of orbit	Sun-Synchronous/ Sub-Recurrent	Sun-Synchronous	Shuttle LEO
Repeat cycle	8 -46 days/2 days	3-35 days	8 days

The main utilities of the 1.25 GHz SARs in addition to capabilities of observation day and night are as follows:

– observation of deformation of land surface through vegetation;
– observation of deformation of land surface near an earthquake's epicentre;
– observation under all weather conditions, including rain;
– observation of volcanoes;
– observation of forestry;
– observation of ice;
– observation of floods;
– observation of oil spills.

Earthquake

Deformation of land surface due to an earthquake can be measured through vegetation by using the differential interferometric method. This method was applied to a huge earthquake which occurred in Shisen, China, on 12 May 2008 as shown in Table 4-3. It was found that the length of the signal path decreased by about 50-60 centimetres (maximum) in the area at the immediate south of the epicentre. This means deformation of the Earth's crust, or diastrophism, took place there. In this case, because the path shortened, the Earth's surface rose.

Forestry

This image in Table 4-3 shows the Riau province of eastern Sumatra where there is remarkable deforestation indicated by the pale purple colour. These areas will be monitored twice a year.

Flood

Table 4-3 shows a colour composite image of the pre- and post- disaster images.

Oil outflow

Table 4-3 shows oil outflow in the neighbourhood of the scene of the accident observed on 11 December 2007. Since the oil area is relatively flat, this shows a dark area in the imagery.

Ice

Table 4-3 shows ice cracking and moving off the coast during a year from August 2007 and June 2008.

TABLE 4-3

Applications of 1.25 GHz SARs

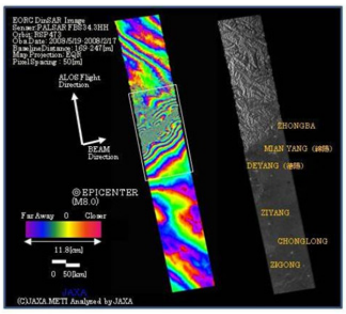
Application	Example	Description
Earthquake		Figure shows diastrophism by processing the image data of SAR imagery taken on 20 May 2008, and one also taken by the PALSAR on 17 February 2008 using the differential interferometric method. The change in the distance between the ALOS spacecraft and the Earth in about three months between 17 February and 20 May is indicated by the two-dimensional colours in the image.

TABLE 4-3 (*continued*)

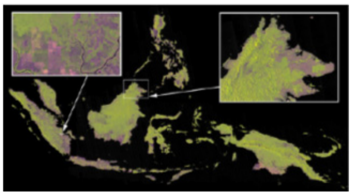
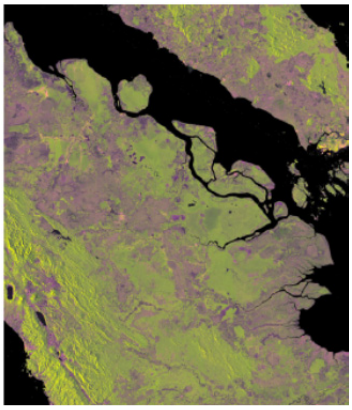
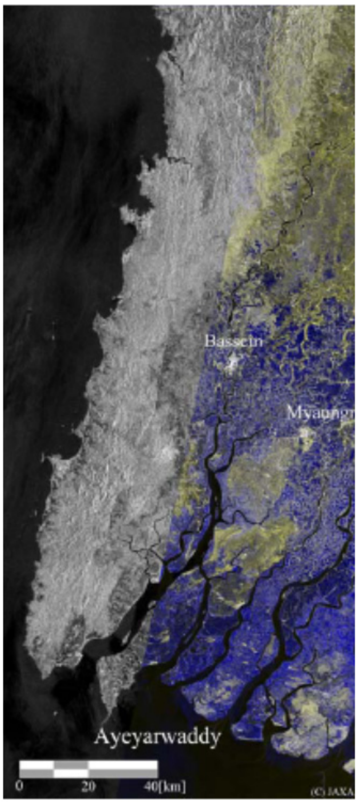
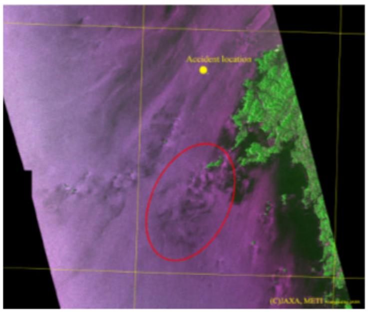
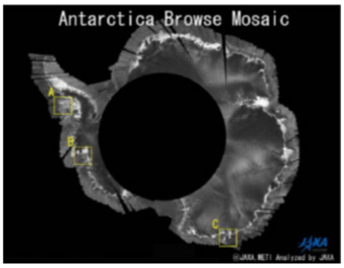
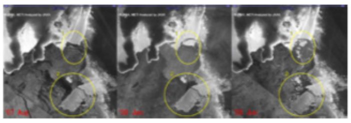
Application	Example	Description
Forestry	 	First figure is colour composite of R= HH polarization, G=HV polarization, B=HH-HV polarization image. Greenish colour shows a forest and purple colour shows either a deforested area or an area which is not a forest. Second figure below is expanded image of part of first figure.
Flood		Figure is a colour composite of imagery before and after a flood, within a 13 day periods. The blue colour shows widespread flooding.

TABLE 4-3 (*end*)

Application	Example	Description
Oil outflow		Figure shows that the dark area inside the red circle is oil outflow. It is an enlarged image of the neighbourhood of the scene of the accident using a polarimetry image of the 11 December 2007 observation.
Ice	 	The upper figure is a mosaic of PALSAR images for the period 8 December 2007 to 22 January 2008 around Antarctica. The white area is very bumpy and the black area is smooth. The images in the lower panel depict changes in a coastal region of the Pine Island glacier at the root of the Antarctica peninsula. From left to right the images are for August 2007, January 2008 and June 2008. During the year spanning these pictures, ice cracked and migrated off the coast.

4.1.1.2 5.3 GHz SARs

The typical characteristics of 5.3 GHz SARs are shown in Table 4-2 with ranges of parameter values including characteristics of RadarSat, ASAR and ERS 1/2.

The ground movement of Turtle Mountain, Canada, after a large landslide is shown in Fig. 4-3; the data are from Canada's RADARSAT-1 using the InSAR technique. As of 2010, the remaining portion of Turtle Mountain, Canada after the largest landslide in recorded history in North America is still a threat.

4.1.1.3 9.6 GHz SARs

The typical characteristics of 9.6 GHz SARs are shown in Table 4-4 with ranges of parameter values including the characteristics of the example SAR X-SAR.

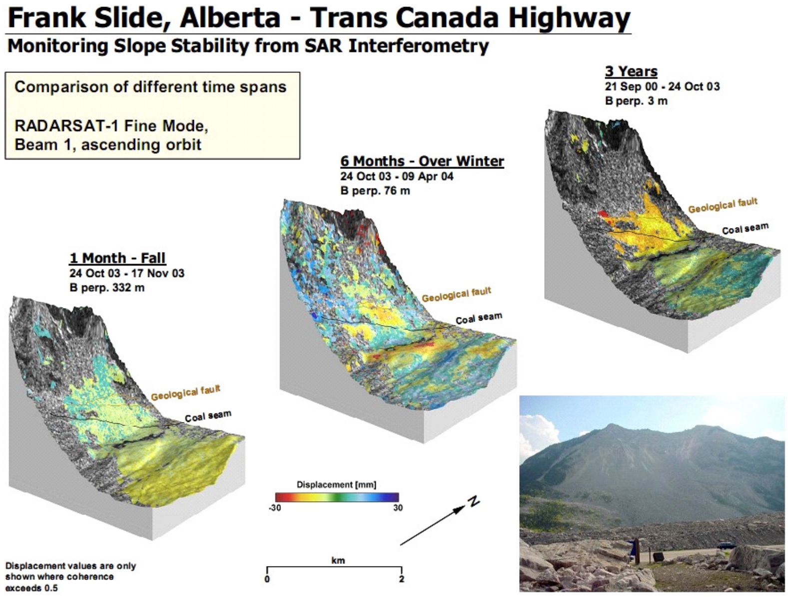
Figure 4-3 shows a quick-look demonstration of the SRTM DEM with a 30 km x 30 km area of the East Allgaeu around the royal castles of Neuschwanstein and Hohenschwangau.

4.1.2 Altimeters

Altimeters provide the height of the Earth's ocean surface. Figures 4-5 a) and 4-5 b) are an illustration of a satellite altimeter's typical return echo. The choice of RF centre frequency depends on the ocean surface interaction with the electromagnetic field. Dual frequency operation enables compensation for ionospheric delays. For instance, the use of frequencies around 13.6 GHz and 5.3 GHz is one such dual frequency arrangement. The wide RF bandwidth affects the height measurement accuracy. The time difference accuracy, Δt, is inversely proportional to BW, where BW is the RF bandwidth.

FIGURE 4-3

RADARSAT InSAR tracks ground displacement between 2000-2004

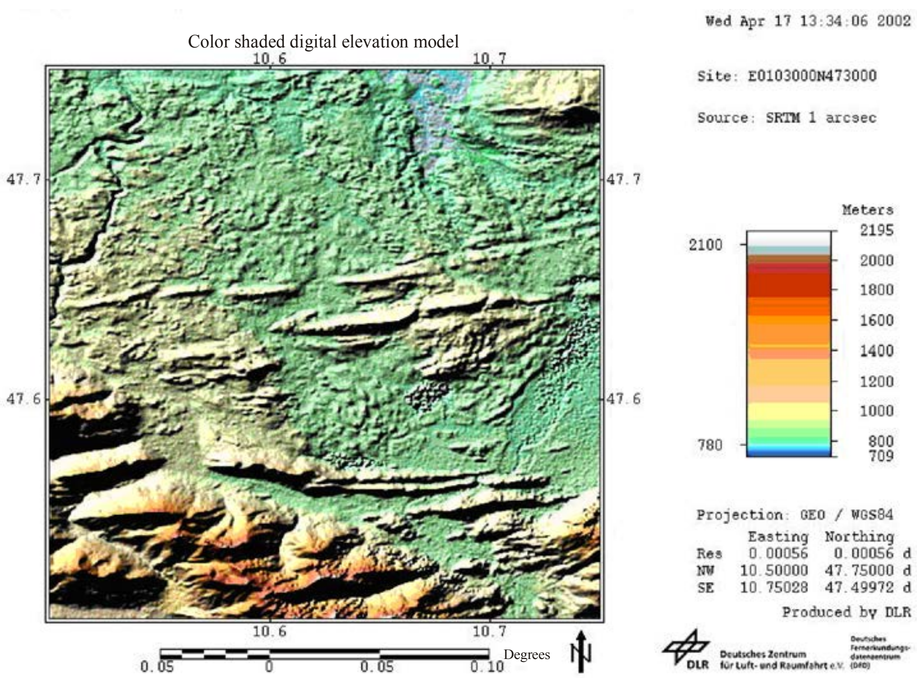


EESS.4-03

Source: RADARSAT via CSA at:
http://www.isprs.org/publications/related/ISRSE/html/papers/759.pdf

FIGURE 4-4

A quick-look demonstration of the SRTM DEM:
30 km x 30 km area showing the east allgaeu around
the Royal Castles of Neuschwanstein and Hohenschwangau

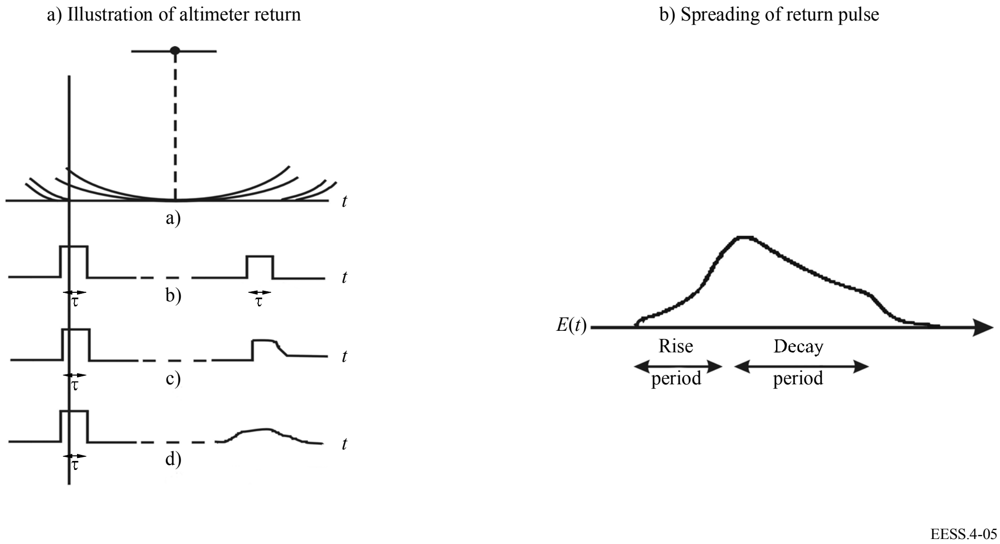


EESS.4-04

SRTM X-SAR via DLR at: http://www.dlr.de/srtm/level1/demo_en.htm

FIGURE 4-5

Illustration of altimeter return and spreading of return pulse



Equation (4-4) calculates the return power from a pulse-limited altimeter:

$$P_R = \frac{P_T G^2 \lambda^2 C_G \sigma_0 \pi c\ \tau}{(4\pi)^3 h^3 L_{RF} L_{atmos}} \tag{4-4}$$

where:

- P_R: altimeter return power level from the Earth's surface (W)
- P_T: radar transmit power (W)
- G: antenna gain
- λ: wavelength (m)
- C_G: compression gain
- σ_0: backscatter coefficient of ocean surface
- c: speed of light (m/s)
- τ: compressed pulse width (s)
- h: altitude (m)
- L_{RF}: system losses
- L_{atmos}: atmospheric losses.

The allowable height accuracy degradation determines the allowable interference level. A 4% degradation in altimeter height noise yields $I/N = -3$ dB.

Some satellite altimeters have measured ocean topography to an accuracy of 4.2 cm. Examples of altimeters in two separate frequency bands are the Jason-1 and TOPEX/POSEIDON altimeters in the 5 140-5 460 MHz and the Jason-1 and ERS 1/2 altimeters in the 13.25-13.75 GHz band.

4.1.2.1 5.3 GHz altimeter

The typical characteristics of the 5.3 GHz altimeter are shown in Table 4-4 with ranges of parameter values including the characteristics of the examples of Jason-1 and TOPEX/POSEIDON altimeters.

TABLE 4-4

Typical characteristics of 5.3 GHz and 13.5 GHz altimeters

Parameter	5.3 GHz altimeter	13.5 GHz altimeter
Antenna type	1.2 m diameter reflector	1.2 m diameter reflector
Frequency	5.3 GHz	13.575-13.8 GHz
Peak power	8.4-14.8 dBW	12-18 dBW
Antenna peak gain	33.2-37.8 dBi	41-42 dBi
Pulsed bandwidth	100 MHz, 320 MHz	20-330 MHz
Pulse width	105 μs LFM	20-105 μs LFM
Altitude	1336 km	764-1336 km
Look angle	nadir	Nadir
Repeat cycle	10 days	10-35 days

4.1.2.2 13.5 GHz altimeter

The typical characteristics of the 13.5 GHz altimeter are shown in Table 4-4 with ranges of parameter values including the characteristics of example altimeters Jason-1, Envisat RA-2 and ERS-1/2.

Figure 4-6 shows an ERS-2 altimeter image of November 16-17, 2000, showing the village of Log pod Mangartom, Slovenia, hit by a massive landslide.

4.1.3 Scatterometers

Ocean scatterometers provide the wind direction and speed over the Earth's ocean surface. The choice of RF centre frequency depends on the ocean surface interaction with the EM field and its variation over aspect angle. Figure 4-7 shows the variation of backscatter level with aspect angle relative to the wind velocity vector direction. In the figure, the scattering return is highest when the angle relative to the wind velocity vector (aspect angle) is 0° (looking forward) and 180° (looking aft). The figure shows 2 cycles when viewing all 360° in a complete rotation about nadir vector of the scatterometer antenna. So fitting a 2 cycle sinusoidal to the measured scattering data would leave us with a 180° ambiguity that can be solved by whether the Doppler returns are positive or negative (wind coming toward us or away from us). The ocean surface wave direction is normally aligned with the wind direction.

As shown in Fig. 4-8, a typical scatterometer illuminates the Earth's surface at several different fixed aspect angles. In Fig. 4-9, the scatterometer scanning pencil beam illuminates scans at two different look angles from nadir, and scans 360° about nadir in azimuth. The narrow RF signal bandwidth provides the needed measurement cell resolution.

Figure 4-10 shows an example radar image taken from the NSCAT scatterometer of the Amazon rainforest in South America. Other examples of scatterometers used for meteorological purposes are the ERS AMI (wind mode) and METOP.

Equation (4-5) calculates the return power from a scatterometer:

$$P_R = \frac{P_T G^2 \lambda^2 A C_{AZ} C_R \sigma_0}{(4\pi)^3 R^4 L_s} \qquad (4\text{-}5)$$

where:

P_R: scatterometer return power level from the Earth's surface (W)

P_T: radar transmit power (W)

G: antenna gain

λ: wavelength (m)

A: pixel area (m^2)

C_{AZ}: azimuth compression gain

C_R: range compression gain

σ_0: backscatter coefficient of Earth's surface

R: range to pixel (m)

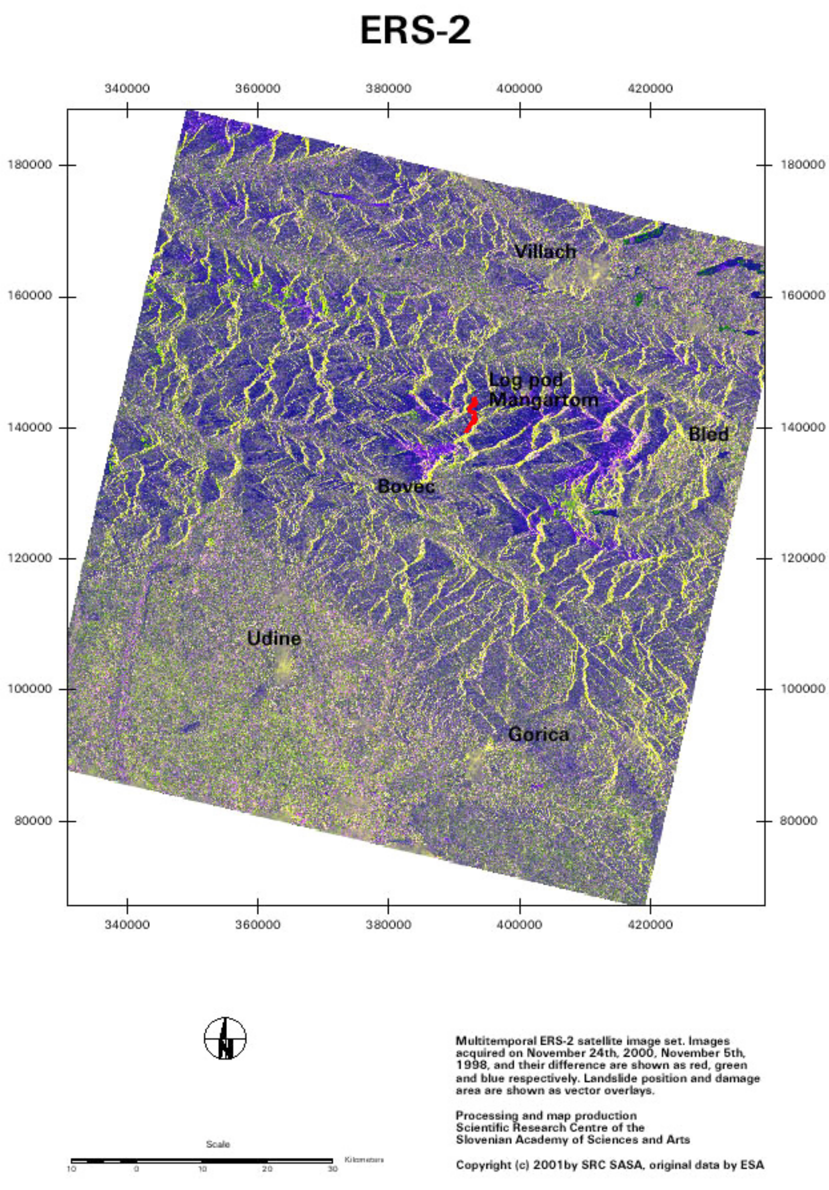
L_S: system losses.

For the scatterometer, the degradation in the measurement of normalized radar backscatter coefficient with simulations of measurement scheme yields $I/N = -5$ dB.

Examples of scatterometers in two separate frequency bands are the Aquarius scatterometer in the 1215-1300 MHz band, and the Seawinds scatterometer in the 13.25-13.75 GHz band.

FIGURE 4-6

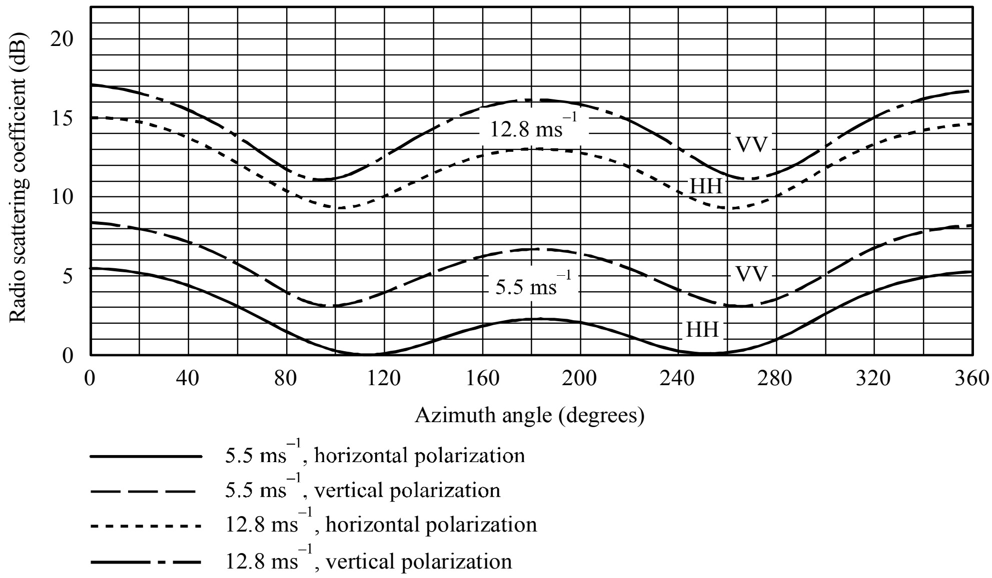
ERS-2 altimeter image of massive landslide in the village of Log pod Mangartom, Slovenia



EESS.4-06

FIGURE 4-7

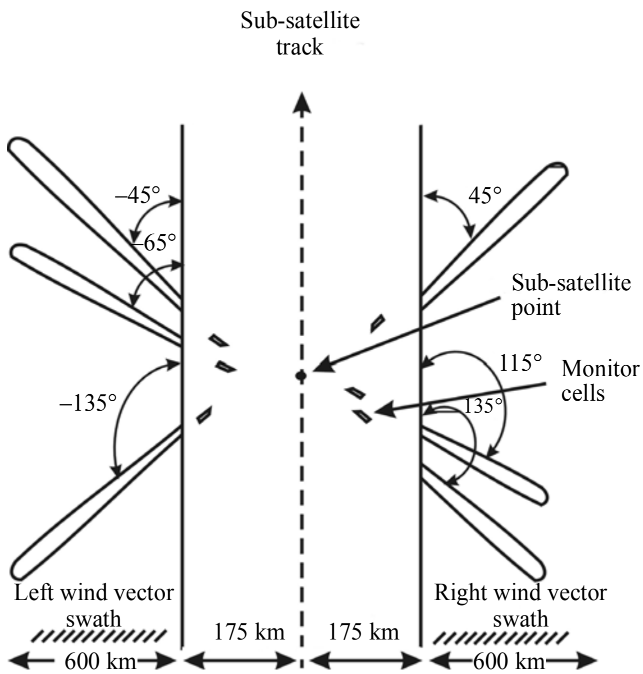
Variation of backscatter with aspect angle for 5.5 m/c and 12.8 m/c wind speeds



EESS.4-07

FIGURE 4-8

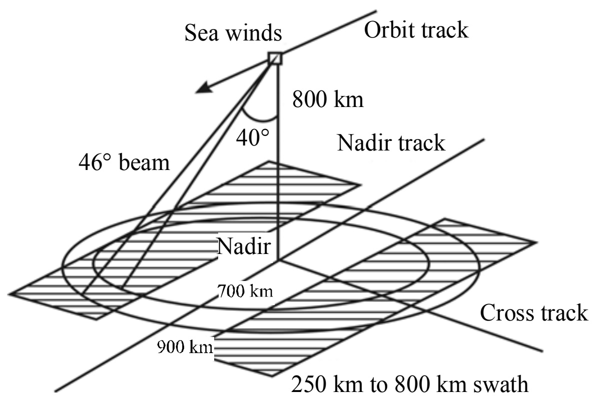
Scatterometer fixed footprint



EESS.4-08

FIGURE 4-9

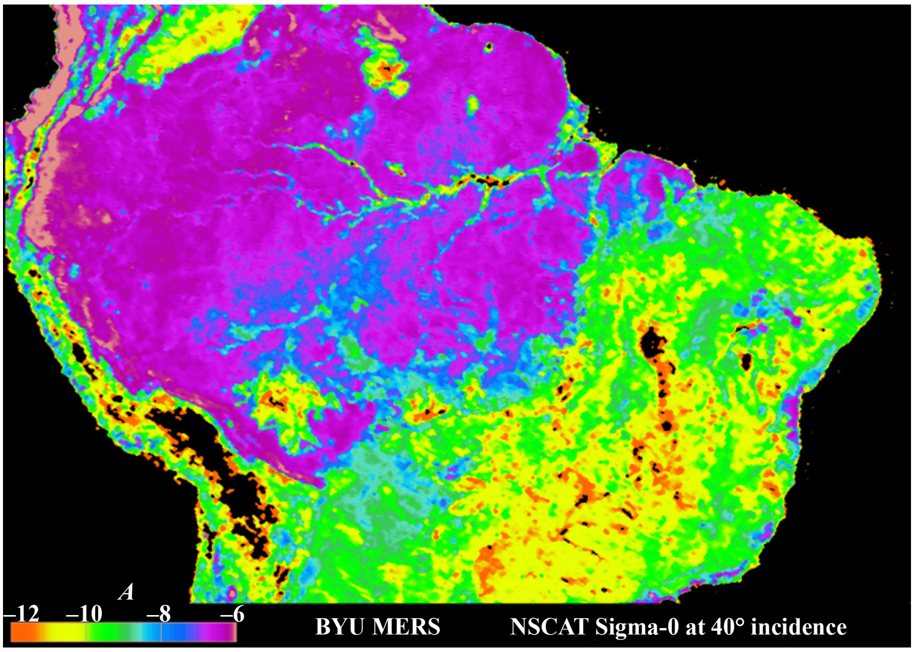
Scatterometer pencil beam scan



EESS.4-09

FIGURE 4-10

NSCAT scatterometers radar image of the Amazon rainforest in South America



EESS.4-10

4.1.3.1 13.4 GHz ocean scatterometer

The typical ocean scatterometer, operating around 13.4 GHz, infers the ocean surface wind speed and direction from measurements of the ocean surface backscatter coefficient from several different azimuth angles as the antenna beams rotate about nadir. Table 4-5 shows the characteristics of the 13.4 GHz scatterometer with ranges of parameter values including the characteristics of the Seawinds ocean scatterometer.

TABLE 4-5

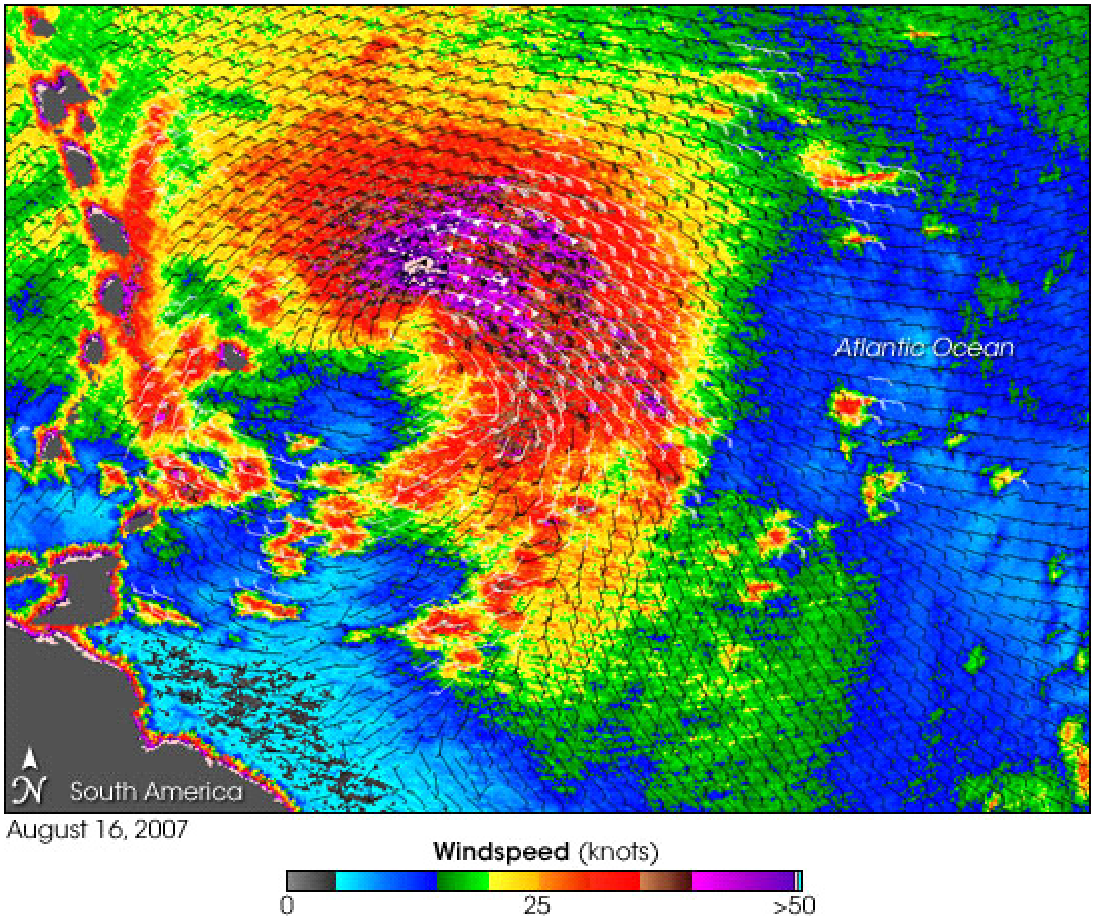
Typical characteristics of 13.4 GHz ocean scatterometer and 1.25 GHz land scatterometer

Parameter	13.4 GHz ocean scatterometer	1.25 GHz land scatterometer
RF centre frequency	13.402 GHz	1215-1300 MHz
Transmit pulsewidth	1.5 ms at 185 Hz PRF	10-1000 μs at 10-3200 Hz PRF
Altitude (km)	813	657-670
Inclination (degrees)	98.615	98
Look angles (degrees)	40 (H-pol) 46 (V-pol)	26-40
Antenna gain (dBi)	39	28-36
Transmit power (W)	110	200

Figure 4-11 shows a QuikScat observation of Hurricane Dean revealing the sea surface wind speed and direction. The combination of data from these and other satellites helps to provide a better understanding of the nature of each hurricane and helps to predict where, when and how strong the hurricane will be in the near future.

FIGURE 4-11

QuikScat observation of Hurricane Dean



EESS.4-11

Source: Scatterometer on QuikScat at:
http://www.nasaimages.org/luna/servlet/detail/nasaNAS~10~10~74747~180271:Hurricane-Dean

4.1.3.2 1.25 GHz ocean and land scatterometer

A typical 1.25 GHz scatterometer measures the ocean surface backscatter coefficient from several different azimuth angles as the antenna beams rotate about nadir and then infers the ocean surface wind speed and direction. The companion radiometer is the primary instrument for measuring sea salt salinity, and the scatterometer provides a correction for surface roughness, which is the largest unknown in the retrieval algorithm.

Over land, 1.25 GHz radar backscatter corresponds to a mixture of surface and volume scattering associated with the radar penetration depth. The surface roughness, vegetation cover and terrain dielectric properties play an important role in determining what the dominant backscatter regime is. The response of the land surface to the radar with respect to incidence angle (slope) is different for both regimes. Hence examining not only the backscatter intensity but also the backscatter slope allows assessing surface type, vegetation cover and soil moisture content.

Table 4-5 shows the characteristics of the typical 1.25 GHz land scatterometer with ranges of parameter values including the characteristics of the Aquarius and SMAP land scatterometers.

4.1.4 Precipitation radars

Precipitation radars (PR) provide the precipitation rate over the Earth's surface, typically concentrating on rainfall in the tropics. The choice of RF centre frequency depends on the precipitation interaction with the EM field. The backscatter cross section of a spherical hydrometeor is shown in equation (4-6):

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

where:

- $|K_W|^2$: related to the refractive index of the drop's water
- D: diameter of the drop (m)
- λ: wavelength of the radar (m)
- Z: radar reflectivity factor.

The backscatter increases as the fourth power of the RF frequency. Equation (4-7) gives the expression for calculation of the return power level of the precipitation.

$$\widetilde{P} = \frac{\pi^5 10^{-17} P_r G^2 t \theta_r^2 |K_W|^2 Z_r}{6.75 \times 2^{14} (\ln 2) r_0^2 \lambda^2 l^2 l_r} \quad \text{mW} \qquad (4\text{-}7)$$

where:

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

As illustrated by this equation, the return power decreases with the square of the wavelength. Since frequency is inversely proportional to the wavelength, the return power increases with the square of the RF frequency. In the case of small particles (Rayleigh regime), the return power increases as the frequency to the power of four since the ratio depends on the relative particle size with respect to the wavelength.

The narrow RF signal pulse-width of the precipitation radar provides the needed measurement range resolution. One example of precipitation radar uses a pulse width of 1.6 µs, though the value may vary with other systems. The allowable minimum precipitation reflectivity degradation determines the allowable interference level. For the precipitation radar, a 7% increase in minimum rainfall rate yields $I/N = -10$ dB.

As examples of precipitation radars in two separate frequency bands are the tropical rainfall measurement mission (TRMM) and global precipitation mission/Dual precipitation radar (GPM/DPR) in the 13.25-13.75 GHz band and GPM/DPR in the 35.5-36.0 GHz band.

4.1.4.1 13.6 GHz (Ku-band) and 35.5 GHz (Ka-band) precipitation radars

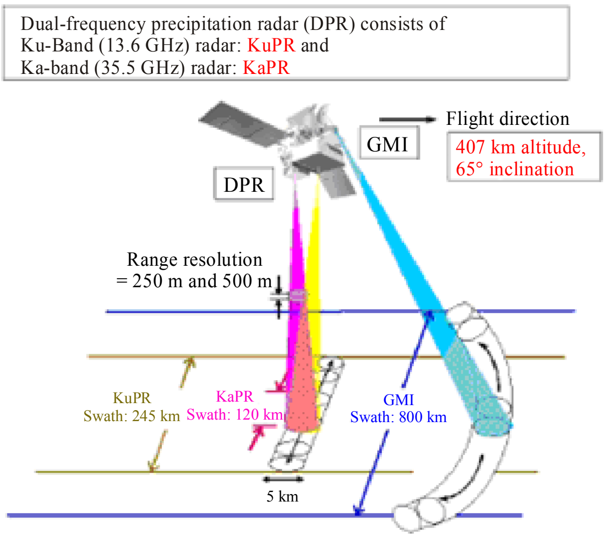
Unprecedented data obtained by one on-board precipitation radar have attracted increased attention and expectations, and have brought us new information on rainfall. The configuration of observations made by precipitation radars is shown in Fig. 4-12.

The TRMM precipitation radar measured tropical and subtropical rainfall. The GPM is more advanced mission and is designed to make more accurate and frequent observation of rainfall by expanding its observing areas to higher latitudes and carries a dual-frequency precipitation radar (DPR) using the 13.6 GHz band and the 35.5 GHz band. Typical characteristics of 13.5 GHz and 35.5 GHz PRs are shown in Table 4-6 with ranges of parameter values including the characteristics of the TRMM and DPR for the 13.5 GHz PR and the DPR for the 35.5 GHz PR.

While the 35.5 GHz PR has high-sensitivity to detect weak rain or snow, the 13.5 GHz PR can detect heavy rainfall. By combining the 13.5 GHz and 35.5 GHz PRs, we can observe accurate rainfall rate in the range from weak rain or snow in the high-latitude regions to strong rainfall in the tropics. The high frequency microwaves used by the PRs are affected by rain attenuation in general. The amount of attenuation depends on the frequency and the size of raindrops. Therefore, we can estimate the drop size distribution (DSD) of rain using the difference of attenuation between the two frequencies 13.5 GHz and 35.5 GHz. To obtain the difference of attenuation, simultaneous observation of precipitation at the same location is required. The DSD information, which cannot be obtained by the existing 13.5 GHz PR, is useful to improve the accuracy of the rainfall estimation. Also, the difference of attenuation may be used for distinction between rain and snow.

FIGURE 4-12

Configuration of observation by precipitation radars



EESS.4-12

TABLE 4-6

Typical characteristics of precipitation radar

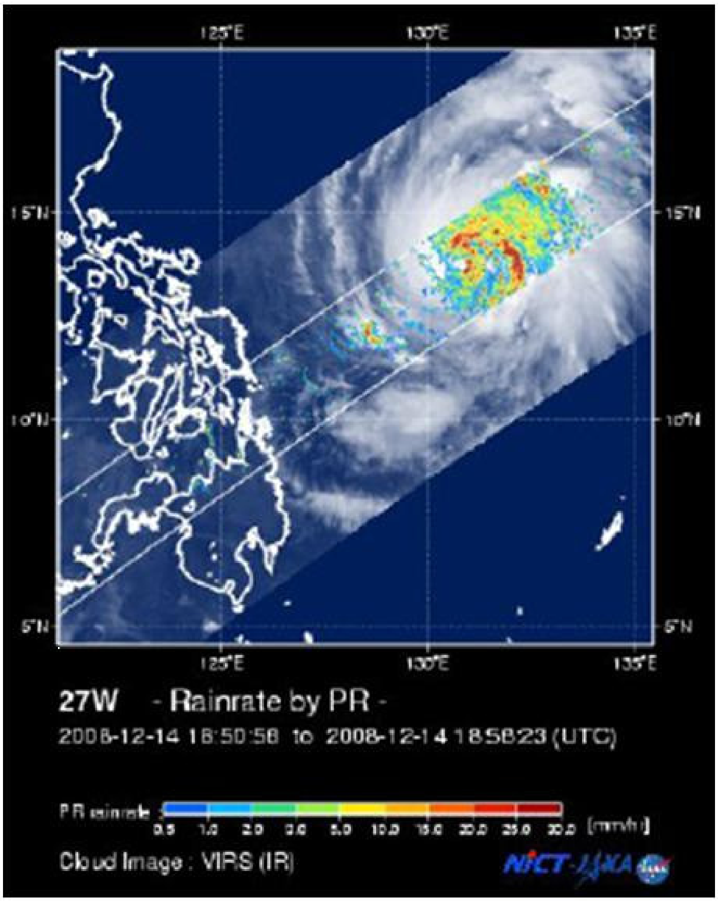
	Precipitation radars (PRs)	
	13.5 GHz PR	**35.5 GHz PR**
Type	Active phased array	Active phased array
Frequency (Bandwidth)	13.597-13.796 GHz (14 MHz) 13.603-13.802 GHz (14 MHz)	35.547 GHz (14 MHz) 35.553 GHz (14 MHz)
Peak powe (W)	500-1000	140
Altitude (km)	350-407	407
Swath width (km)	215-245	125
Antenna gain (dBi)	47.4	47.4

4.1.4.2 Some results of the application of precipitation radars

Figure 4-13 shows rain rate distribution of a Typhoon near Philippines on 14 December 2008.

FIGURE 4-13

Rain rate observed by TRMM PR



EESS.4-13

4.1.5 Cloud profile radars

Cloud profile radars (CPR) provide a three dimensional profile of cloud reflectivity over the Earth's surface. Figure 4-14 shows a representative backscatter reflectivity versus altitude. Examples of CPRs are the Cloudsat CPR and the EarthCARE CPR, both in the 94.0-94.1 GHz band.

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

Equation (4-8) gives the expression for calculation of the return power level of the clouds.

$$\widetilde{P} = \frac{\pi^5 10^{-17} P_r G^2 t \theta_r^2 |K_W|^2 Z_r}{6.75 \times 2^{14} (\ln 2) r_0^2 \lambda^2 l^2 l_r} \quad \text{mW} \tag{4-8}$$

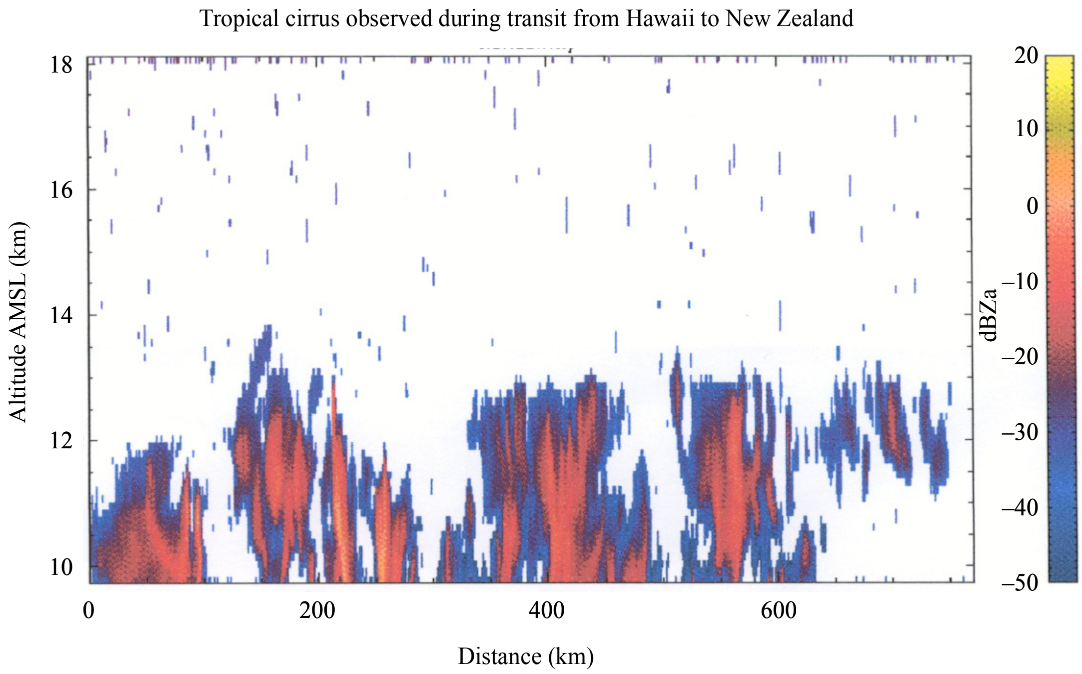
where:

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

As illustrated by this equation, the return power decreases with the square of the wavelength. Since frequency is inversely proportional to wavelength, the return power increases with the square of the RF frequency. In the case of small particles (Rayleigh regime), the return power increases as the frequency to the power of four since the ratio depends on the relative particle size with respect to the wavelength. The cloud profile radar antennas have very low sidelobes so as to isolate the cloud return from the higher surface return illuminated by the sidelobes. For the cloud profile radar, a 10% degradation in minimum cloud reflectivity yields $I/N = -10$ dB.

FIGURE 4-14

Example of cirrus cloud reflectivity



EESS.4-14

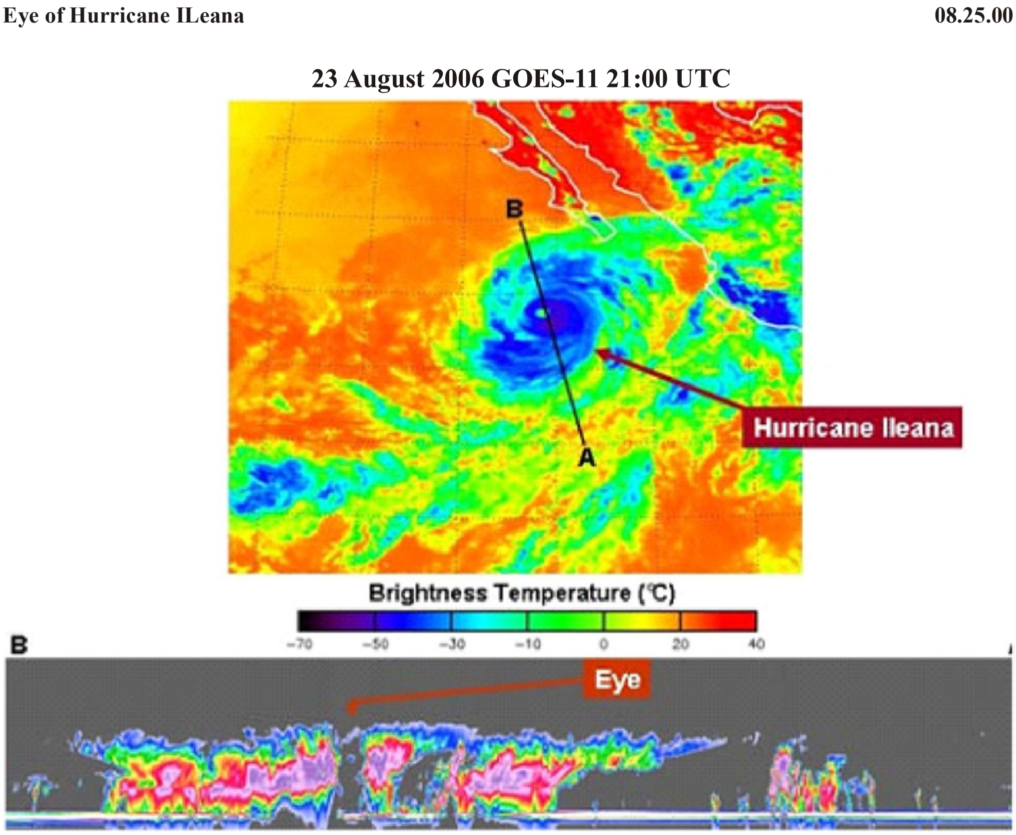
4.1.5.1 94 GHz cloud profile radar

The 94 GHz cloud profile radar provides a global survey of cloud profiles and cloud physical properties, with seasonal and geographical variations, that are needed to evaluate the way clouds are parameterized in global models, thereby contributing to improved prediction of weather, climate and the cloud-climate feedback problem.

Figure 4-15 shows a Cloudsat image of radar profiles of clouds around Hurricane Ileana on August 23, 2006. The top image is from NOAA's GOES to show the storm from the top. The bottom image is a cross section of cloud reflectivity along the line A-B shown in the top image.

FIGURE 4-15

Cloudsat image of cloud profiles around Hurricane Ileana on August 23, 2006



EESS.4-15

Other spaceborne CPRs will use the Doppler information from the radar and have Doppler speed sensor functions. Through this function, we can understand not only the vertical structure of clouds, but also the vertical motion within cloudy regimes. Table 4-7 shows typical characteristics of the 94 GHz CPR with ranges of parameter values including the characteristics of example CPRs Cloudsat and EarthCare at 94 GHz.

4.2 Preferred frequency bands and bandwidths for active sensors

The preferred frequency bands and bandwidths are provided in Recommendation ITU-R RS.577 for the various types of active spaceborne sensors.

4.3 Active sensor interference and performance criteria

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

TABLE 4-7

Typical characteristics of 94 GHz cloud profile radar

Parameter	Value
Frequency	94.05 GHz
Peak power (nominal)	1.8 kW
Altitude	400-705 km
Orbital inclination	97-98.2°
Pulse width	3.3 μs
PRF	4340 Hz to >6100 Hz
Antenna type	Parabolic reflector to Offset cassegrain antenna
Antenna diameter	1.85-2.5 m
Antenna gain	63.1-65.2 dBi
Beam direction	Nadir
Beam width	0.095-0.108°
Vertical resolution	250-500 m
Horizontal resolution	0.7-1.9 km
Minimum sensitivity	–30 to –35 dBZ
Doppler range	±10 m/s
Doppler accuracy	1 m/s

4.4 Sharing considerations for active sensors

The sharing considerations for sharing between spaceborne active sensors in the EESS (active) and other services are provided in Recommendations ITU-R RS.1260, ITU-R RS.1261, ITU-R RS.1280, ITU-R RS.1281, ITU-R RS.1282, ITU-R RS.1347, ITU-R RS.1628, ITU-R RS.1632 and ITU-R RS.1749. These Recommendations are concerned with specific frequency bands or ranges of frequencies and the other services operating in those bands.

The sharing considerations for spaceborne active sensors include the level of the power flux-density and received interference power at the Earth's surface, the type of transmitted RF signal, the dynamics of the antenna coupling with systems of other services, and the types of systems in the other service.

4.4.1 Power-flux density levels and received interference power levels

The characteristics of the various types of active spaceborne sensors as shown in Table 4-1 indicate that the transmitted peak power and therefore the power levels received at the Earth's surface will vary significantly. Table 4-8 shows the active sensor power flux density levels at the Earth's surface for some typical sensor configurations. From Recommendation ITU-R RS.1280, the average interfering signal power level, I (dBW), received by terrestrial radars from a spaceborne active sensor is calculated from equation (4-9):

$$I = 10 \log P_t + 10 \log(\tau \, PRF) + G_t + G_r - (32.44 + 20 \log(fR)) + OTR - PG \tag{4-9}$$

where:

- P_t: peak spaceborne sensor transmitter power (W)
- τ: spaceborne sensor pulse width (s)
- PRF: spaceborne sensor pulse repetition frequency (Hz)
- G_t: spaceborne sensor antenna gain towards terrestrial radar (dBi)
- G_r: terrestrial radar antenna gain towards spaceborne sensor (dBi)
- f: frequency (MHz)
- R: slant range between sensor and radar (km)
- OTR: radar receiver on-tune rejection (dB)
- PG: processing gain (dB), rejection of unwanted signals due to radar receiver signal processing (assumed to be zero if not known).

TABLE 4-8

Typical power flux-density levels at Earth's surface

Parameter	Sensor type				
	SAR	**Altimeter**	**Scatterometer**	**Precipitation radars**	**Cloud profile radars**
Radiated power (W)	1 500	20	100	578	630
Antenna gain (dB)	36.4	43.3	34	47.7	63.4
Range (km)	695	1 344	1 145	350	400
PFD (dB(W/m^2))	–59.67	–77.25	–78.17	–46.55	–31.64

4.4.2 Types of RF signal waveforms

The types of RF signal waveform transmitted by the active sensors are shown in Table 4-1. All five types of active sensors use pulsed waveforms. The SARs, altimeters, and land scatterometers typically use linear FM pulses, whereas, the ocean scatterometers, precipitation radars, and cloud profile radars typically use unmodulated pulses. In general, pulsed sources share compatibly with other pulsed systems, such as terrestrial radars. From Recommendation ITU-R RS.1280, on-tune rejection OTR is calculated from the following equations for an input pulse with frequency modulation as specified in equations (4-10a) and (4-10b):

$$OTR = 10 \log \left(\frac{B_r^2 \tau}{B_c} \right) \quad \text{for} \quad \frac{B_r^2 \tau}{B_c} < 1 \qquad \text{(4-10a)}$$

$$= 0 \quad \text{for} \quad \frac{B_r^2 \tau}{B_c} > 1 \qquad \text{(4-10b)}$$

where:

- B_r: terrestrial radar IF bandwidth
- B_c: chirp bandwidth of spaceborne sensor
- τ: sensor pulse width.

4.4.3 Dynamics of antenna coupling with systems of other services

The viewing geometry and footprint/dynamics of the active sensors are shown in Table 4-1. All five types of active sensors are mounted on spacecraft looking down at the Earth's surface. The SARs have a look angle, that angle between nadir and the beam centre, of 10° to 55°. The scatterometers look off at an angle of about 40° from nadir. The altimeters, precipitation radars and the cloud profile radars are nadir looking. Typical terrestrial search radars cover low elevation angles, and do not have mainlobe-to-mainlobe coupling in elevation.

The sensor beams scan past the terrestrial systems as the spacecraft proceeds in its orbit. For a sensor beamwidth of 2°, the beam scans past the terrestrial system in about 2-3 seconds. The SARs typically look down to the side of the nadir track either at a commanded look angle or at various look angles for ScanSAR modes. The altimeters are typically nadir looking. The scatterometers are either fixed at various azimuth angles or are conically scanned about nadir with one or more beams. For a sensor beamwidth of 2°, the conically scanning beam scans past the terrestrial system in less than 25 milliseconds for a scan rate of 15 rpm. Typical terrestrial search radars also scan 360° in azimuth at rates of 5 to 10 rpm so that the terrestrial radar beam with a 1-degree beamwidth scans past the spaceborne sensor in only 30 to 60 milliseconds. The precipitation radars typically are nadir looking and scan across the nadir track. For a sensor beamwidth of 0.7°, the cross-track scanning beam of the precipitation radar scans past the terrestrial system in only 12.5 milliseconds at a scan rate of about 57 degrees/second. The cloud profile radars are typically nadir looking.

4.4.4 Types of systems in other services

The types of systems in the other services affect the sharing feasibility with spaceborne active sensors. Table 4-9 shows what other services are also operating systems in bands allocated to the EESS (active). In general, active sensors with pulsed waveforms can share the same frequency band with other active pulsed systems, such as terrestrial search and tracking radars in the radiolocation service. The RNSS receivers are compatible with active sensors with low duty cycles. In the 1215-1260 MHz band, the RNSS receiver phase-tracking loop SNR is degraded approximately by the effective duty cycle. For example, a SAR with a 2% effective duty cycle degrades the RNSS receiver by only about 0.1 dB.

TABLE 4-9

Other services operating in frequency bands used by EESS (active) systems

Frequency band (MHz)	EESS (active) allocation status	Other services in band	Sharing considerations by service and by band see Recommendation ITU-R
432-438	Secondary	RADIOLOCATION, AMATEUR, amateur satellite, FIXED, MOBILE,ISM, SPACE OPERATION SERVICE (EARTH-TO-SPACE), aeronautical radionavigation	RS.1260: wind profiler radars, space object tracking radars, launch vehicle range safety command destruct receive frequency RS.1282: avoid FM pulsed wind profiler radars RS.1347: slight increase in loop SNR of RNSS receiver RS.1749: mitigation techniques to share with radiolocation and radionavigation radar systems
1215-1300	Primary	RADIOLOCATION,RNSS, Amateur (secondary)	RS.1280 : processing gain of search radars Slight increase in loop SNR of RNSS receiver
3100-3300	Secondary	RADIOLOCATION	RS.1280: processing gain of search radars
5250-5460	Primary	RADIOLOCATION (active and secondary), AERONAUTICAL RNSS	RS.1280: processing gain of search radars RS.1632: sharing feasible with RLANs having constraints
5460-5570	Primary	RADIOLOCATION	RS.1280: processing gain of search radars
8550-8650	Primary	RADIOLOCATION	RS.1280: processing gain of tracking radars

TABLE 4-9 (*end*)

Frequency band (MHz)	EESS (active) allocation status	Other services in band	Sharing considerations by service and by band see Recommendation ITU-R
9 300-9 800 9 800-9 900	Primary Primary	RADIOLOCATION, RADIONAVIGATION Fixed	RS.1280: processing gain of tracking radars Compatible with fixed, but only for bandwidths > 500 MHz
13 250-13 750	Primary	AERONAUTICAL RNSS, RADIOLOCATION	RS.1281: Constraints on EESS (active) for "short dwell" and "long dwell"
17 200-17 300	Primary	RADIOLOCATION	
24 050-24 250	Secondary	RADIOLOCATION, Amateur (secondary)	
35 500-35 600	Primary	RADIOLOCATION, MET-AIDS, FIXED, MOBILE	RS.1628: Constraint on pfd of EESS (active) to share with radiolocation radars, compatibility with fixed service
78 000-79 000	Primary	RADIOLOCATION, Amateur, Amateur-satellite, Space research (space-to-Earth)	
94 000-94 100	Primary	RADIOLOCATION	RS.1261: mitigation technique to protect radio astronomy in 86-92 GHz, feasible to share with radiolocation, limit band to cloud profile radars
133 500-134 000	Primary	RADIOLOCATION	
237 900-238 000	Primary	RADIOLOCATION	

CHAPTER 5

SPACEBORNE PASSIVE MICROWAVE SENSORS OPERATING IN THE EARTH EXPLORATION-SATELLITE SERVICE (PASSIVE)

5.1 Passive sensors

Passive sensing involves only the use of receivers, with no transmitters involved. The signals sought by these receivers are the background signal (i.e., noise) floors that occur naturally, usually at very low power levels, and which contain essential information on the physical processes under investigation. Of interest are peaks in the background signal indicating the presence of specific chemicals, or the absence of radiation from certain frequencies indicating the absorption of the frequency signals by atmospheric gases. The strength or absence of signals at particular frequencies is used to determine whether specific gases (moisture and pollutants being obvious examples) are present and if so, in what quantity and at what location. Additionally, the brightness patterns over the Earth's oceans and land masses provide key information on fundamental dynamic processes driving ocean circulation and diurnal land interactions with the atmosphere above it.

A wide variety of environmental information can be sensed through passive sensors in frequency bands determined by fixed physical properties (molecular resonance) that cannot be changed, nor are these physical properties necessarily able to be duplicated in other bands. Signal strength at a given frequency may depend on several variables, making the use of several frequencies necessary to solve for the multiple unknowns. The use of multiple frequencies, including multiple channels around a single frequency, is the primary technique used to measure various characteristics of the atmosphere and surface of the Earth.

All matter emits, absorbs and scatters electromagnetic energy. Passive sensors measure the electromagnetic energy emitted and scattered by the Earth and the chemical constituents in its atmosphere. Passive microwave sensors are radiometers which are low noise receivers patterned after radio astronomy instruments. The microwave power these sensors measure is a function of the composition, physical temperature, roughness, and other physical characteristics of objects in its field of view.

Passive sensing products are derived from microwave radiometric measurements. In selected microwave bands, the deviation of measured radiometric energy from the theoretical black-body radiation is used to identify various parameters on the Earth's surface and its atmosphere, which are the passive sensor products. Satellite-borne passive sensors capture the radiation emitted from the Earth and its atmosphere. Objects such as the Earth's surface, vegetation, water particles, and atmospheric gases radiate at unique frequencies that depend on the temperature of the object. This radiation is called thermal radiation because of its temperature dependence.

A black body is matter that absorbs all incident electromagnetic radiation. None of the incident radiation passes through, or is reflected from, the matter. The object does, however, radiate energy. According to Kirchhoff's Law, the radiated energy from an object in thermal equilibrium with its surroundings equals the absorbed energy, and this energy depends only on the temperature T (in degrees Kelvin). Since a black body radiates more energy than other matter at a given temperature, it is called a perfect radiator. At microwave frequencies, the Rayleigh-Jeans radiation law governs the intensity of the radiation emitted by a unit surface area into a given direction from a black body. This law can be expressed in many forms, one of which is:

$$E(\lambda, T) = \frac{2kT}{\lambda^2} \qquad (5\text{-}1)$$

where:

E: the radiance emitted ($W/(m^2 \cdot Hz \cdot sr)$)

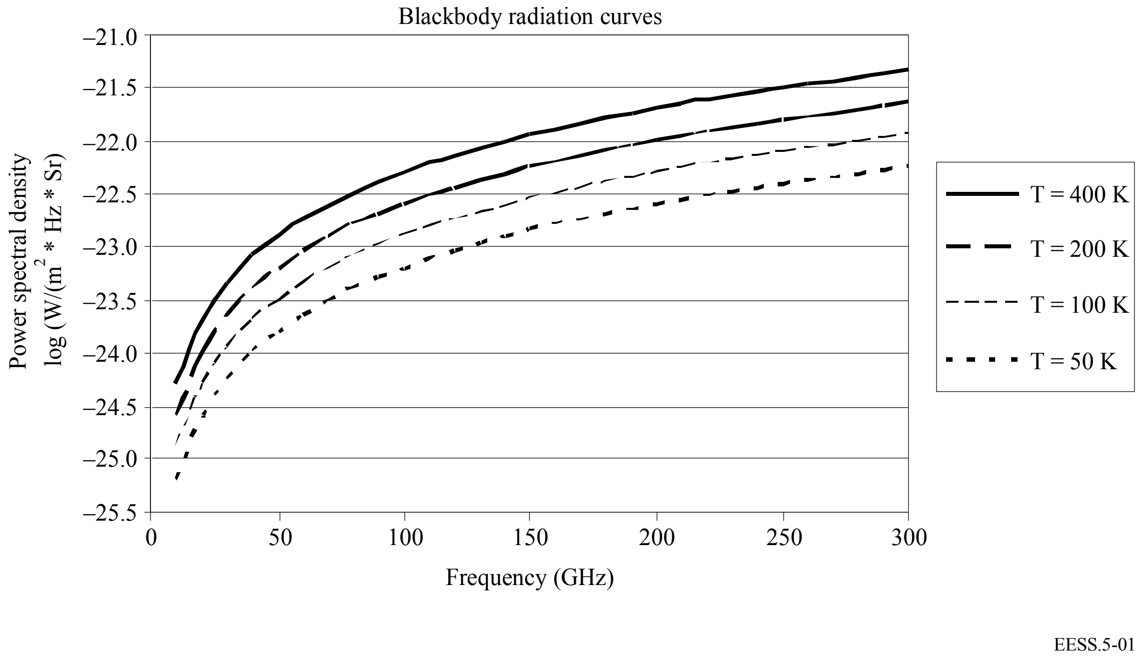
k: Boltzmann's constant = 1.38×10^{-23} ($W \cdot Hz^{-1} \cdot K^{-1}$)

λ: the wavelength (m).

Figure 5-1 depicts the Rayleigh-Jeans law at microwave frequencies for several temperatures that are in the operating range of microwave sensors. As can be seen, the spectral power density in the microwave region increases with frequency. Therefore, power in the microwave spectrum is relatively low compared to the power in the infrared and visible spectra.

FIGURE 5-1

Rayleigh-Jeans law of radiation



Microwave sensors measure radiation, which can be expressed either in terms of power or temperature. Background radiation is contributed by the radiometer as well as the Earth and its atmosphere. Processing on the ground removes the radiometric noise contributed by the radiometer itself, leaving only useful data.

The following discussion applies to the Earth's surface, but can be easily extended to its atmosphere.

Ideally, the sensor measures only the power radiated from a "resolution cell" on the Earth's surface. This cell, sometimes called the antenna "footprint," is defined by the intersection of the sensor antenna's main beam with the Earth's surface. The magnitude of this measured power can be calculated as follows. If the radiation source were isotropic (i.e., radiated equally in all directions), the radiated power per unit area of the surface per unit frequency interval would be:

$$4\pi E(\lambda, T) = \frac{8\pi kT}{\lambda^2} \qquad \text{W/(m} \cdot \text{Hz)} \tag{5-2}$$

Assume for simplicity that the sensor antenna is nadir-pointing, although it can be shown that the results also apply for antennas pointing off nadir. If A is the area of the sensor antenna's footprint on the Earth's surface, then the power per unit frequency isotropically radiated from that area is:

$$4\pi E(\lambda, T)A = \frac{8\pi kTA}{\lambda^2} \qquad \text{W/Hz} \tag{5-3}$$

Sensor antennas have high beam efficiencies, implying that most (typically about 95%) of the received power arrives from the footprint. In this situation, the antenna gain G is related to the antenna footprint area as follows:

$$G = \frac{4\pi d^2}{A} \tag{5-4}$$

Where d is the distance of the sensor antenna from its footprint. Finally, the free-space loss between the footprint and the sensor antenna is:

$$L = \left(\frac{4\pi d}{\lambda} \right)^2 \tag{5-5}$$

Combining these factors, the power per unit frequency received by the sensor is:

$$\frac{1}{2} \times \frac{8\pi kTA}{\lambda^2} \times \frac{4\pi d^2}{A} \times \left(\frac{\lambda}{4\pi d} \right)^2 = kT \qquad \text{W/Hz} \tag{5-6}$$

The factor ½ accounts for the fact that the sensor is sensitive to only one polarization. Therefore, the radiation power density measured by the sensor is simply kT ($\text{W} \cdot \text{Hz}^{-1}$). This says that the sensor is essentially measuring the black-body temperature of the Earth's surface. Of course, this is not completely correct because the Earth is not a black body. The black-body temperature must be modified by the emissivity of the Earth's surface and by the effects of the intervening atmosphere. In addition, even though sensor antennas have high beam efficiencies, radiation nevertheless arrives at the sensor from areas outside the sensor antenna footprint. The latter effect can be accounted for by considering the measured temperature to consist of contributions from all directions relative to the sensor antenna, integrated over 4π steradians:

$$T = \frac{1}{4\pi} \int_{\Omega} G(\Omega) T(\Omega) \, d\Omega \tag{5-7}$$

Where $d\Omega$ is an incremental solid angle subtended at the antenna. Processing on the ground adjusts the measured temperature to account for the fact that the antenna beam efficiency is not 100%.

Real objects are not perfect radiators, and can be referred to as grey bodies because they radiate less energy than a black body. The ratio of the energy radiated by an object to the energy of a black body at the same temperature as that object is called the emissivity ε, and has a range of 0 to 1. Emissivity depends on the dielectric constant of the object, surface roughness, temperature, wavelength, look angle, etc. The temperature of a black body that radiates the same energy as an observed object is called the brightness temperature of that object, T_B. Disregarding effects of the intervening atmosphere, the physical temperature and brightness temperature are related by:

$$T_{B,N} = \varepsilon T \tag{5-8}$$

Where $T_{B,N}$ is the brightness temperature, neglecting atmospheric effects.

The surface of the Earth is the primary source of thermal radiation in window channels. Oceans and lakes have a low but relatively consistent intensity of radiation. Land areas have higher intensities but these intensities are more variable because of the texture of objects, shape, moisture content, vegetation, and mineral content.

The constituents of the atmosphere (gases and aerosols) modify the brightness temperature further. Radiation transfer through the atmosphere can be classified into multiplicative and additive effects. The multiplicative effect refers to the amount by which energy from the Earth to the sensor is reduced due to atmospheric absorption and scattering. Absorption occurs at those wavelengths at which electromagnetic energy excites atmospheric molecules to different energy states. Atmospheric gases have absorption bands that are specific to the molecule. For example, the H_2O molecule has absorption bands around 22.3 GHz and 183.31 GHz. The O_2 molecule has several absorption bands between 50 and 60 GHz and a single band at 118.75 GHz. "Windows" are areas of the microwave spectrum where the influence of atmospheric gases is minimal and radiation from the Earth can reach the sensor with little attenuation.

In addition to atmospheric absorption, scattering from atmospheric constituents also occurs. Scattering is frequency dependent, and its effect is to further reduce the energy at the sensor at high frequencies. Absorption and scattering occur at the same time, so both effects must be considered in deriving meteorological parameters. These multiplicative effects can be accounted for by introducing a loss factor L_{atm} so that the brightness temperature becomes:

$$T_{B,A} = L_{atm} T_{B,N} = \varepsilon L_{atm} T \qquad (5\text{-}9)$$

where $T_{B,A}$ is the brightness temperature considering atmospheric attenuation.

The additive effect refers to thermal emission from the atmospheric constituents themselves. It is more complicated than the multiplicative effects because:

1. it depends on the atmospheric pressure, which in turn is a function of temperature and moisture;
2. emission in lower layers of the atmosphere can be re-absorbed, re-emitted, and scattered in the upper layers.

For simplicity, the additive effects will be accounted for by defining T_{atm} to be the effective brightness temperature of the atmosphere, and adding it to brightness temperature given above, so that:

$$T_B = T_{B,A} + T_{atm} = \varepsilon L_{atm} T + T_{atm} \qquad (5\text{-}10)$$

where T_B is the brightness temperature measured by the radiometer.

It is the quantity kT_B, not the black-body result kT, which is the actual radiated power density measured by the sensor. A more detailed treatment, which sometimes incorporates scattering and emission from rain drops, yields what is known as the radiation transfer equation.

5.1.1 Imaging sensors

Many meteorological and surface environmental data products are produced using multivariable algorithms to retrieve a set of geophysical parameters simultaneously from calibrated multi-channel microwave radiometric imagery. For example, sea-surface temperature, wind speed, water vapour, and cloud water are simultaneously estimated using multi-channel imagery. If one or more bands were removed from the imagery set, the ability to perform the multivariable estimate would be inhibited. In general terms, frequency bands from about 6 GHz to greater than 183 GHz are used for the generation of microwave-based imagery.

5.1.2 Atmospheric sounding sensors

Atmospheric sounding is a measurement of vertical distribution, or profile, of physical properties within a column of the atmosphere such as pressure, temperature, wind speed, wind direction, liquid water content, ozone concentration, pollution, and other properties. Vertical atmospheric sounders (i.e., instruments that take atmospheric sounding measurements) are nadir-looking sensors, which are used essentially to retrieve vertical atmospheric temperature and humidity profiles. They use frequency channels carefully selected within the absorption spectra of atmospheric O_2 and H_2O. Because the distribution of oxygen in the atmosphere is known and doesn't vary significantly, measurements around an oxygen line can be used to derive the atmospheric temperature profile, or temperature as a function of altitude. Measurements around a water line, however, are used to determine the atmospheric humidity profile, or water vapour as a function of altitude.

5.1.3 Microwave limb sounding sensors

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

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

– the vertical resolution is determined by the radiative transfer through the atmosphere and by the vertical field of view of the antenna;

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

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

– the space background is optimum for emission measurements.

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

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

5.2 Spectrum requirements and scientific use of frequency bands

Several geophysical parameters generally contribute, at varying levels, to natural emissions, which can be observed at a given frequency. Therefore, measurements at several frequencies in the microwave spectrum must be made simultaneously in order to isolate and to retrieve each individual contribution. The absorption characteristics of the atmosphere are characterized by absorption peaks due to the molecular resonance of atmospheric gases, and by the water vapour continuum which increases significantly with frequency. Figure 5-2 shows attenuation for a standard atmosphere (water vapour concentration of 7.5 g/m^2) and for dry atmosphere (water vapour concentration of 0 g/m^2).

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

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

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

5.2.1 Observation over ocean surfaces

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

Figure 5-3 shows the sensitivity of brightness temperature to geophysical parameters over ocean surfaces that:

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

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

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

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

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

5.2.2 Observation over land surfaces

Remote sensing over land surfaces is somewhat more complex due to the high temporal and spatial variability of surface characteristics (from snow/ice covered areas to deserts and tropical rain forest). Moreover, the signal received by the passive sensor has been propagated through a number of different media: basically the soil, perhaps snow and/or ice, the vegetation layer, atmosphere and clouds, and occasionally rain or snow. The second factor to be taken into account is the fact that for each medium, several factors might have an influence on the emitted radiation. For instance, the soil will have a different brightness temperature depending on the actual soil temperature, soil moisture content, surface roughness, and soil texture. Similarly, the vegetation contribution will be related to the canopy temperature and structure through the opacity and single scattering albedo (i.e., the ratio of reflected to incident radiant energy). The ways that these factors affect the signal are frequency interdependent. Figure 5-4 depicts the normalized sensitivity as a function of frequency for several key parameters.

FIGURE 5-2

Zenith opacity of the atmosphere due to water vapour and dry components

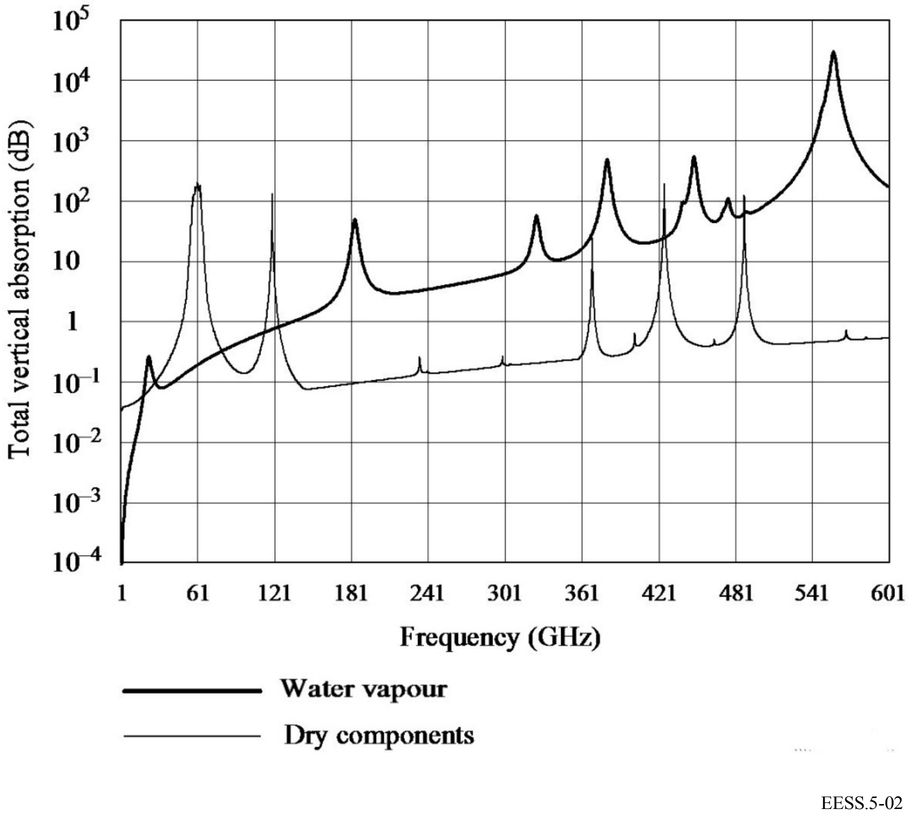


FIGURE 5-3

Sensitivity of brightness temperature to geophysical parameters over ocean surface

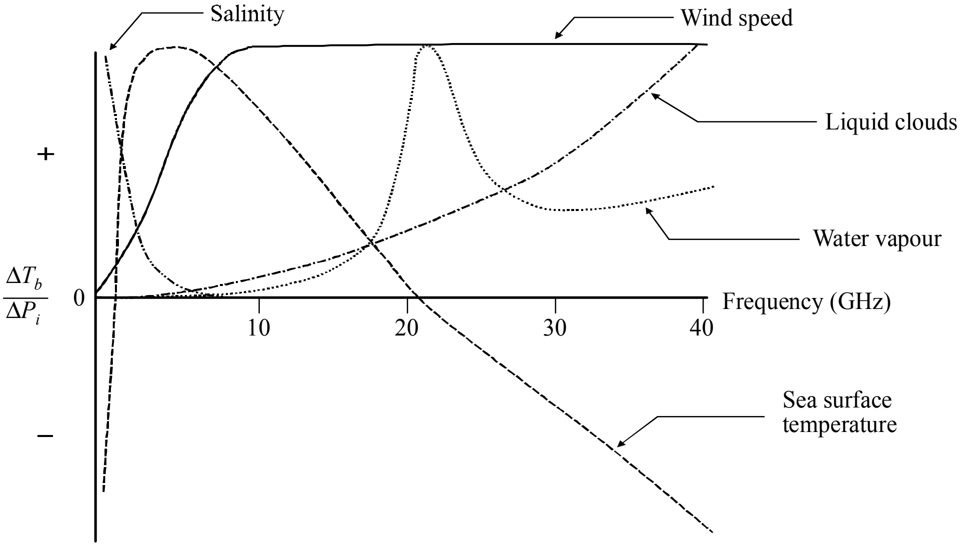


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FIGURE 5-4

Sensitivity of brightness temperature to geophysical parameters over land surfaces

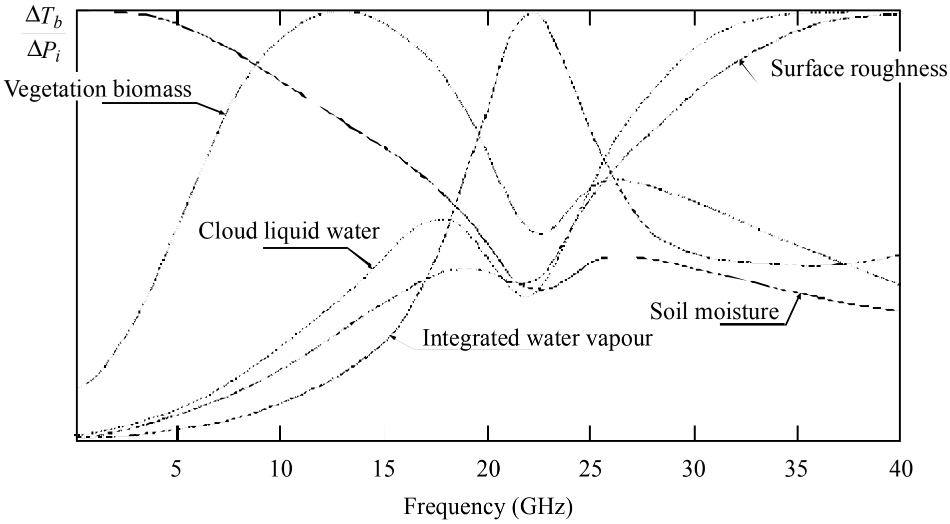

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Figure 5-4 shows that over land and for an average temperate area, it is necessary to have access to:

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

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

– two frequencies around the water vapour absorption peak (typically 18-19 GHz and 23-24 GHz) to assess the atmospheric contribution;
– a frequency around 37 GHz to assess cloud liquid water (with use of 18 GHz), and/or vegetation structure (with 10 GHz) and surface roughness (with 1 GHz and 5 GHz or 10 GHz).

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

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

Snow covered areas are important to monitor and here again the necessity for several frequencies is crucial. Actually snow and ice must be distinguished as well as the snow freshness. The related signal is linked to the structure of the snow layers and the crystal sizes. To retrieve such information it has been shown that several frequencies are required, usually 19 GHz, 37 GHz and 85-90 GHz.

5.2.3 Observation of atmospheric constituent gases

There are many gases in the atmosphere that have a direct impact on the Earth's environment, including its climate. Measurement of these gases can be accomplished using either nadir or limb scan modes.

5.2.3.1 Nadir

Nadir scan modes concentrate on sounding or viewing the Earth's surface at angles of nearly perpendicular incidence (i.e., looking straight down from the satellite). The scan terminates at the surface or at various levels in the atmosphere according to weighting functions which represent the contributions of different layers. Nadir scans are most frequently used to measure atmospheric temperature and water vapour in bands below 200 GHz.

5.2.3.2 Limb sounding

Limb scan modes view the atmosphere "on edge" and terminate in space rather than at the surface, and accordingly are weighted zero at the surface and maximum at the tangent point height (i.e., looking at the Earth's limb or up from the horizon rather than down). Many atmospheric trace gases associate with atmospheric chemistry can best be monitored using limb soundings. Such gases include bromide monoxide (BrO), carbon monoxide (CO), carbon dioxide (CO_2), chlorine monoxide (ClO), hydrochloric acid (HCl), hydroxyl (OH), methyl chloride (CH_3Cl), methyl bromide (CH_3Br), nitric acid (HNO_3), nitrous oxide (NO), nitrous dioxide (N_2O), ozone (O_3) and sulphur dioxide (SO_2). Use of limb sounding instruments is generally limited to frequencies above 100 GHz.

5.2.4 Frequency bands of interest

There are a number of frequency bands allocated for passive use, many in which all other emissions are prohibited in accordance with RR No. 5.340. Most of these bands are used by passive sensors flown on Earth exploration satellites to measure various atmospheric and surface properties of the Earth and to monitor the temporal changes of these properties which reflect the changing environment and climate of the Earth. The most significant bands and their associated environmental parameters are briefly described in the following subsections.

5.2.4.1 1 400-1 427 MHz

The 1 400-1 427 MHz band is allocated exclusively for passive remote sensing and is extremely important for land and ocean measurements. In particular, it is one of the few frequency bands where information on ocean salinity can be obtained. Additionally, this band provides soil moisture content data in combination with other frequencies, since the depth of soil moisture measurement is dependent on frequency. Other parameters that are measured in this band include snow form and structure (the morphology of snow), sea ice thickness and ocean sea state. This information can be applied to areas such as agricultural and marine food production, water resources, hazard warning, ship routing and weather forecasting.

5.2.4.2 6425-7250 MHz

Ocean surface temperatures can be readily determined using this band. Unfortunately, the band is not allocated for passive sensing use, but measurements over the open oceans are less likely to suffer from interference. Other useful measurements, but of a lesser importance include soil moisture content, ocean sea state and sea ice thickness. Applications of these data include long range weather forecasting, fishery resources and the associated deployment of fishing vessels.

5.2.4.3 10.6-10.7 GHz

This band is primary importance for a number of parameters including snow morphology, rain rate, sea and lake ice morphology and estuarine sea state. Valuable applications from these measurements are found in ship routing, weather forecasting, winds over oceans and hazard warning. The lower portion of the sub-band, 10.6-10.68 GHz, is shared with active services and is therefore susceptible to interference in inhabited regions. The upper portion of the band, 10.68-10.7 GHz, is exclusively allocated for passive sensing and other passive services.

5.2.4.4 18.6-18.8 GHz

The major parameters obtained from passive observations using this band include rain rate, sea state (for wind speed) and sea ice morphology. Applications of these parameters include weather forecasting, ship routing and hazard warning. Passive sensors receiving emissions in this band must be concerned with possible interference from active services allocated on a co-primary basis. Though limitations exist on these active services, some interference may be observed over regions where the density of active transmitters is high.

5.2.4.5 23.6-24 GHz

This exclusively passive band is a major source for information on water vapour and secondarily for rain rate. Even though all emissions are prohibited, there is some concern from aggregation of very low-level emissions from accident-avoidance radars placed in automobiles. Should these devices proliferate in sufficient numbers, interference may be noted in the data collected by passive sensors. The principal applications of passively sensed data in this band are weather forecasting, climate modelling, and information on the availability of water vapour for condensation and subsequent precipitation.

5.2.4.6 31.3-31.8 GHz

The 31.3-31.5 GHz portion of the band is exclusively allocated to passive services and most currently operational passive sensors restrict their receivers to this 200 MHz sub-band. As with 23.6-24 GHz, this band is also a primary source of water vapour information. Information on sea ice and snow morphology may also be gathered. Applications include short- and long-range weather forecasting, climatological forecasting and ship routing.

5.2.4.7 36-37 GHz

This band is critical for measurement of a host of parameters including rain rate, snow and sea ice morphology, lake ice, snow water content and oil slicks. It is shared on a co-primary basis with active terrestrial services. Power limitations imposed on the active services should ensure interference-free operation of passive sensors. Applications are found for stream flow forecasting, transport, ship routing and pollution.

5.2.4.8 50.2-50.4 GHz

This frequency band is used to measure the Earth’s surface temperature. That measurement is used to calibrate data from higher frequencies used in turn to profile atmospheric temperatures. The band is exclusively passive and further protected from interference by restrictions placed on active services operating in adjacent bands. The sole application is for weather forecasting.

5.2.4.9 52.6-59.3 GHz

Multiple bands are used in this range of frequencies (which includes a cluster of oxygen lines) to provide a profile of atmospheric temperatures up to about 60 km. Such temperature profiles are used operationally providing input to numerical weather forecast models.

5.2.4.10 86-92 GHz

This exclusively passive band provides assessments of clouds, snow and ice morphology and oil slicks with applications for environmental regulations and water resources.

5.2.4.11 109.5-122.25 GHz

Most of this range of frequencies can be used to measure atmospheric temperatures, stratospheric ozone, carbon dioxide (CO_2) and nitrous oxide (NO). Applications are found for weather forecasting, stratospheric air pollution and environmental regulations.

5.2.4.12 148.5-151.5 GHz

Allocated exclusively for passive use, this band provides measurements of stratospheric nitrous oxide (NO). Applications for air pollution and environmental regulations benefit from these data.

5.2.4.13 174.8-191.8 GHz

Sub-bands in this frequency range provide stratospheric ozone and profiles of stratospheric water vapour. These measurements have direct application for forecasting weather, monitoring of stratospheric air pollution, and monitoring adherence to environmental regulations.

5.2.4.14 226-231.5 GHz

This frequency range provides measurements of stratospheric nitrous oxide, ozone and carbon dioxide. These measurements have direct application for monitoring stratospheric air pollution and adherence to environmental regulations.

5.2.4.15 235-1 000 GHz

In this large frequency range, many sub bands are used for monitoring the Earth's atmosphere. Two major groups can be identified, viz., one for applications concerning meteorology and climatology and one for atmospheric chemistry. Within the first group specific applications concern profiling of atmospheric temperatures and water vapour as well as measurements of cloud ice. The atmospheric chemistry emphasis focuses on measuring the various trace gases listed in § 5.2.3.2 and studying the gases effect on the Earth's atmosphere and climate.

5.2.4.16 1 000-3 000 GHz

There are a large number of spectral lines that may be of interest for atmospheric chemistry sounding between 1 000 GHz and 3 000 GHz. Potentially, any frequency above 1 000 GHz could be used for future measurements from satellites. The hydroxyl lines (OH) around 1 836 and 2 508 GHz are identified as lines of particular interest.

The Earth's atmosphere is virtually opaque at frequencies above 1 000 GHz, and limb sounding is the only feasible technique. Between 1 000 and 3 000 GHz, studies show that sharing between EESS and active services should be possible. The strong atmospheric absorption in that region of the spectrum effectively shields passive spaceborne instruments from terrestrial-based active services, while space-based active services have minimal opportunity to cause interference lasting a significant length of time.

5.3 Performance parameters

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

5.3.1 Radiometric sensitivity

Radiometric sensitivity is generally expressed as the smallest temperature differential, ΔTe that the sensor is able to detect. ΔTe is given by:

$$\Delta T_e = \frac{\alpha T_s}{\sqrt{B\tau}} \qquad \text{K} \tag{5-11}$$

where:

- B: receiver bandwidth (Hz)
- τ: integration time (s)
- α: receiver system constant (depends on the configuration)
- T_s: receiver system noise temperature (K).

5.3.2 Radiometer threshold ΔP

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

$$\Delta P = k \Delta T_e B \qquad \text{W} \tag{5-12}$$

where:

- k: Boltzmann's constant = 1.38×10^{-23} (J/K)

ΔP is computed using ΔTe. In the future, Ts will decrease and as will ΔTe (see equation (5-11)). As a result, ΔP must be computed using a reasonable future ΔTe rather than the ΔTe of current technology. In the same manner, the integration time, τ, will likely increase as remote sensing technology develops further (e.g., the so-called "pushbroom" concept). Therefore, the integration time must also be chosen based on reasonable future expectations.

5.3.3 Geometric resolution

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

5.3.4 Integration time

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

5.4 Passive sensor performance and interference criteria

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

5.5 Passive sensor interference and sharing considerations

The fundamental property being measured by a passive instrument is a background radiative emission floor. Any signal that rises significantly above this floor, such as a communications transmission, will likely interfere with data from a passive sensor instrument. This interference can be tolerated only if its energy is much less than the sensitivity of the radiometer.

Passive remote sensors are particularly vulnerable to the accumulated radiation from multiple terrestrial emitters (i.e., aggregate interference), both in and out of the frequency band of interest. Thus, while a single terrestrial emitter may not radiate enough power to cause harm, a large number of these emitters can still be harmful to the measurements being taken through the aggregation of their signals (i.e., the sum from all emitters in the instrument's field of view). This is the basis for concern for applications like high-density fixed service (HDFS) emissions, ultra wide-band (UWB) devices and other devices like short-range and industrial, scientific and medical (ISM) ones. The spatial density of these emitters rather than their individual characteristics creates a problem. As the density increases, the problems may become acute, and some of the issues have been reported.

Even very low levels of interference received by a passive sensor may degrade its data. The biggest threat is that the interference will go undetected and that corrupted data will be mistaken for valid data. Hence, the conclusions derived from the analysis of these corrupted data will be seriously flawed.

Most passive sensors cannot discriminate between natural and man-made radiation, so data errors often cannot be detected and/or corrected. Maintaining data integrity therefore depends upon the prevention of man-made interference. The imposition of strict limitations on such interference and maximum power on a global basis currently appears as the only solution. One can note that a number of provisions in the Radio Regulations use power limits on active service transmitters to protect passive sensors from in-band or out-of-band interference.

CHAPTER 6

SOCIETAL BENEFITS OF THE EARTH EXPLORATION-SATELLITE SERVICE

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6 Introduction

Satellites provide the most cost-efficient way to monitor the land, sea, and air environment of the entire Earth. Unique capabilities of Earth exploration-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. Some of these benefits, such as inputs to weather forecasters, are taken for granted and appreciated only during extreme conditions such as hurricanes; many other benefits go unrecognized. This chapter will highlight many of those societal benefits but will not go into the details of how the data were obtained, processed and used.

6.1 Benefits related to 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, thus creating the need for outside assistance. They can have both natural and man-made sources. The meteorological aids, meteorological-satellite, and Earth exploration-satellite services play a major role in activities such as identifying areas at risk; forecasting weather and predicting climate change; detecting and tracking tsunamis, hurricanes, droughts, forest fires, oil leaks, etc; providing alerting/warning information of such disasters; assessing the damage caused by such disasters; providing information for planning relief operations; and monitoring the recovery from a disaster.

Local in situ, real-time measurements or observations are usually more precise and more accurate than similar observations made from space. However, spaceborne observations can provide information helpful in alleviating the effects of disasters when in situ instrumentation, or the supporting infrastructures necessary to use such instrumentation, are not in place or have been disabled by the disaster, or the ground measurements are not accurate enough. 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.

Examples of how data products from satellites may be useful in alleviating the effects of natural and man-made disasters follow. These examples are brief but plausible; some have been demonstrated while others are operational today. This list is not exhaustive.

6.1.1 Coastal and maritime hazards

Coastal and maritime hazards encompass those hazards occurring on, or bordering on, large bodies of water, such as oceans and large lakes.

6.1.1.1 Sea and lake ice

Satellite-borne passive microwave sensors have mapped sea ice extent for decades, and synthetic aperture radars (SAR’s) are used to map sea and lake ice as well as to operationally extend the shipping season at high latitudes.

6.1.1.2 Tsunamis and rogue (Killer) waves

Spaceborne sensors can help identify areas at risk by using SAR-generated digital elevation models (DEMs) to locate low areas subject to flooding, or by using SAR-generated bathymetry to identify ocean bottom structure that might amplify the incoming tsunami or storm surge.

Severe weather events, such as tropical cyclones (called hurricanes in some areas and typhoons in others) that produce storm surges, are tracked by weather satellites. Such tracking is used to alert vulnerable areas of the potential danger and provide warning when high winds and significant ocean surge and seas are imminent.

The extent of the damage can be determined using moderate- and high-resolution visible/infrared imagery from satellite-borne instruments. SAR imagery, which is unaffected by cloud cover, can also be used to show the damaged areas. 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.

Rogue waves, or “killer” waves, are the open sea counterpart to tsunamis. Tsunamis raise havoc on coastal areas but are benign in the open sea; rogue waves occur only in the open sea. They occur when waves combine, perhaps with other factors such as sea floor topography and ocean currents, to form a huge wave, typically 15-30 meters high. Such waves were believed to be extremely rare, and very few sailors have survived encounters with them. In 1943, the ocean liner Queen Elizabeth 1 encountered a rogue wave that broke windows on the bridge 90 feet (27 meters) above the waterline. With the ocean-wide surveillance capabilities of satellite instruments, particularly SAR’s, the existence of such waves has been confirmed. They were found to not be as rare as previously assumed, and areas prone such waves have been identified. These waves may be responsible for the annual loss of 2% of all ocean-going ships experienced over the last several centuries.

6.1.2 Atmospheric hazards

Atmospheric hazards are driven by weather-related events, such as excessive or minimal rainfall.

6.1.2.1 Droughts

The onset and progress of a drought can be observed from space by noting soil moisture using both active and passive microwave techniques, and by observing rainfall and the distress level of the vegetation (plant vitality, via multi-spectral images) in the affected areas. Long-range predictions of regional drought conditions can be made by tracking the Pacific Ocean temperatures and heights, which give an indication of the onset of an El Niño event, or the opposite condition, a La Niña event.

During an El Niño event, the equatorial eastern Pacific is warmer and the ocean surface is elevated due to thermal expansion. Droughts frequently occur in Australia and Indonesia under these conditions, and the trade winds are weaker. Conversely, during a La Niña event, the equatorial eastern Pacific is cooler and the ocean height is lower due to thermal compression. The western coasts of the Americas experience dry conditions, and the trade winds are stronger. Tracking conditions in the Pacific Ocean from satellites gives warnings months in advance of an El Niño/La Niña event.

6.1.2.2 Dust storms

Dust storms originate over desert or drought-stricken areas and can travel long distances. Such storms can be seen, characterized, and monitored by satellite instruments.

6.1.2.3 Extreme weather – cyclones, hurricanes, typhoons, etc.

Two types of operational meteorological (i.e., weather) satellites scan the entire globe: geostationary satellites and polar satellites. Views from geostationary satellites show an entire hemisphere and are available every 15-30 minutes. Cloud structure, extent, and overall motion of storms are apparent in the imagery (see Fig. 6-1).

The rapidly updated scenes point to likely locations of wind and water damage. Data from these satellites are most valuable at lower latitudes, showing tropical cyclones and their tracks and intensity.

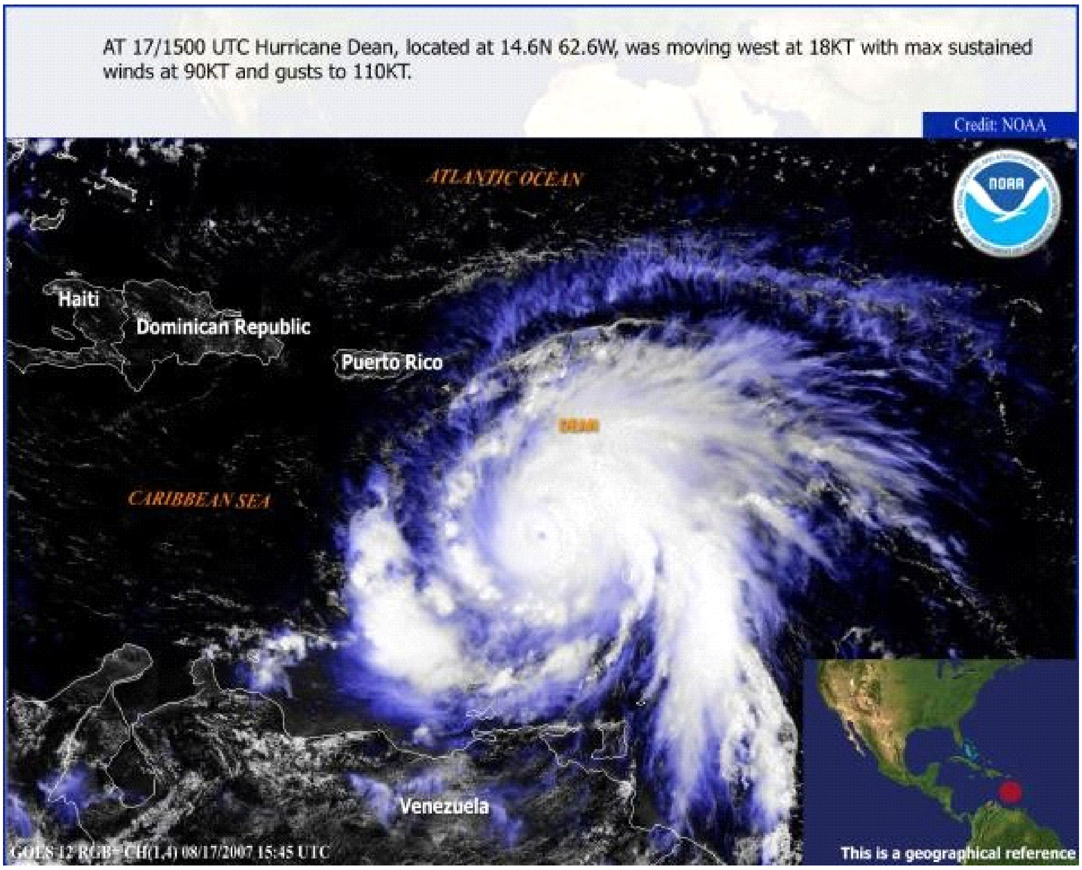
Polar-orbiting satellites typically overfly an area twice a day and provide more detailed, but less timely, observations. For example, radar scatterometers can reveal the sea surface wind speed and direction. Unfortunately, such scatterometers fly on low Earth-orbiting spacecraft and cannot provide the continuous coverage afforded by the GSO observations.

The combination of positional information from geostationary satellites and wind information from their polar-orbiting counterparts gives invaluable data on the structure of tropical cyclones.

One of the very few EESS missions in a low equatorial orbit, the Tropical Rainfall Measurement Mission (TRMM) provides three-dimensional maps of rainfall, including spectacular 3-D maps of rain patterns in hurricanes. Like the polar-orbiting missions, it does not provide continuous coverage.

FIGURE 6-1

Hurricane dean observed from a geosynchronous satellite



EESS.6-01

http://www.nnvl.noaa.gov/cgi-bin/index.cgi?page=products&category=Year%202007%20Storm%20Events&event=Hurricane%20Dean

6.1.2.4 Floods

Long before a flood occurs, the areas vulnerable to being flooded (areas at risk) can be identified with the help of satellite-derived DEMs. DEMs enable the topology of remote low-lying areas to be mapped. 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 indicates whether the ground will absorb more rain or is already saturated.

During a flood event, imagery from multispectral and/or panchromatic 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 is particularly useful during flood-producing storms.

6.1.3 Surface hazards

Surface hazards deal with hazards on the solid surface of the Earth, but exclude events driven or initiated by the atmosphere (e.g., floods and droughts).

6.1.3.1 Earthquakes

After a major earthquake has occurred, the quicker an accurate damage estimate is made, the quicker appropriate rescue assets can be mobilized. Damage-estimate decision support systems are being developed which are based on population density, type of building construction in the affected area, and the location and magnitude of the earthquake. Seismographs can provide the first detection of an earthquake, but interferometric SAR measurements (InSAR), and in situ measurements using the radionavigation-satellite service (RNSS), including such systems as the American Global Positioning System and the Russian GLONASS), provide a far more accurate determination of the location and extent of the rupture for use in estimating the damage.

Usually the ground movements associated with earthquakes are too small to appear in satellite visible or infra-red imagery. However, visual imagery can be very useful for assessing the damage caused by an earthquake and for guiding rescue efforts.

6.1.3.2 Landslides, subsidence and avalanches

Areas vulnerable to landslide activity can be identified using DEMs from SAR measurements. In this case, the slopes rather than the elevations are used. When ground movement is suspected, InSAR and in situ RNSS units can provide measurements accurate enough to monitor subtle ground movement on the order of centimetres.

Changes in land cover or land usage can increase the risk of landslides. For example, a heavily logged (deforested) area is far more susceptible to landslides than an area with an established ecosystem that stabilizes the ground. Land-use maps help quantify the risk by identifying populated areas that may be vulnerable. Land cover/land usage can be monitored from space and changes detected to aid in monitoring the risk.

When soil on steep hillsides becomes saturated with water during a very heavy rainfall, it becomes vulnerable to 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 occurrence, InSAR images can provide an accurate mapping of the ground movement (i.e., 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.

6.1.3.3 Volcanoes

Volcanic activity is frequently preceded by swelling/uplifting of the ground in the immediate area which can be monitored, to some degree, by mapping such ground movements. In situ RNSS units can provide local monitoring while InSAR observations, measuring motions on the order of centimetres, can provide less timely measurements at remote locations. Such subtle ground motions can be used to identify potential volcanic hazards anywhere in the world.

The thermal warming of the immediate area prior to an eruption can also be observed from space. 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, volcanic ash in the atmosphere poses serious hazards to aircraft in flight.

Imaging from satellites supports the identification of impacted areas and the monitoring of recovery.

SAR imagery is also useful in identifying areas at risk. For example, the Pinatubo eruption produced several “lahars” (very fast travelling mud or debris flows which contain volcanic material, rocks, and water), which were easily identified and monitored in SAR images. Because they could be re-activated by heavy rains, nearby inhabited areas may be placed at risk. DEMs have proven useful in predicting where such lahars may occur since the lahars follow gullies and flow into low areas. Such DEMs can be combined with land use/land cover maps to identify areas at risk (see Fig. 6-2).

6.1.3.4 Wildfires

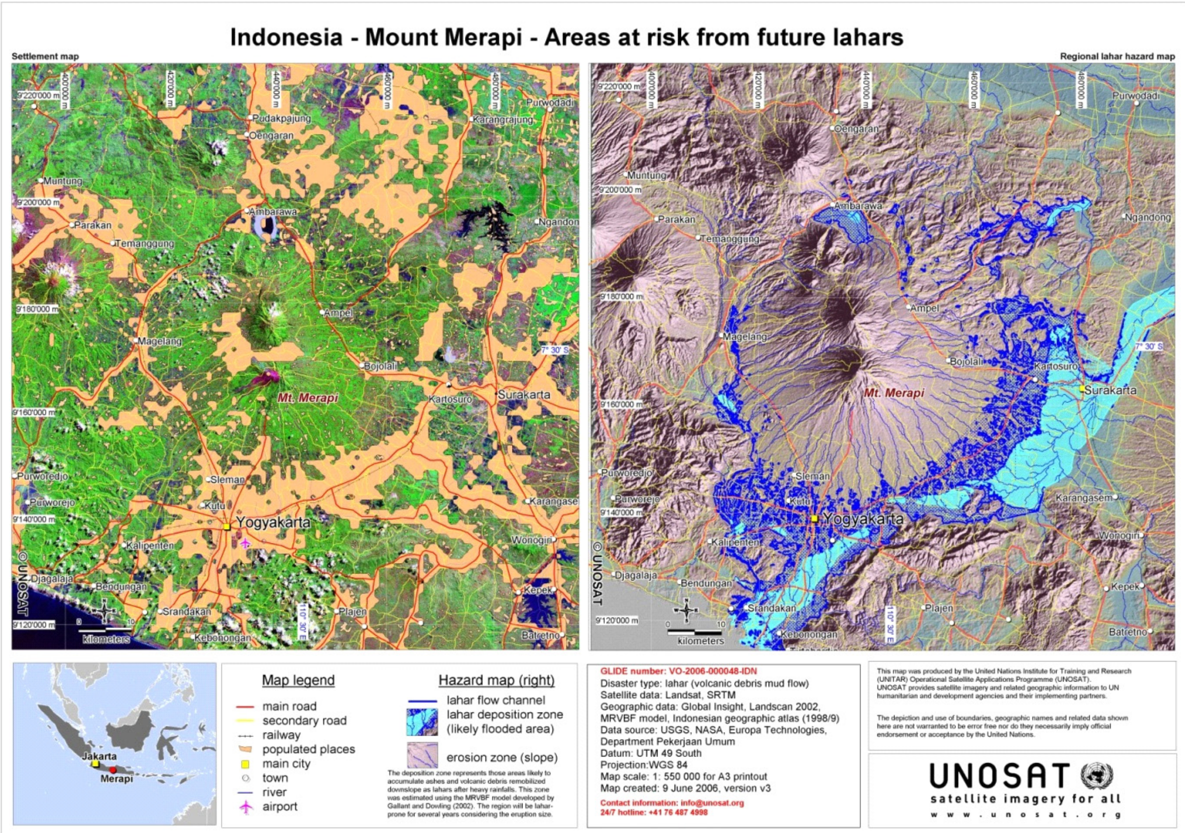
The risk for wild land fires in remote, sparsely populated areas can be estimated from space measurements of soil moisture and vegetative state (i.e., is the vegetation healthy or distressed/parched?).

Wild land fires 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. Such 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.

FIGURE 6-2

Land use map (left, Landsat data) and potential lahar paths (right, shuttle radar DEM data) combine to identify areas at risk from a volcano eruption



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URL: http://unosat.web.cern.ch/unosat/asp/prod_free.asp?id=21

6.1.4 Pollution detection and monitoring

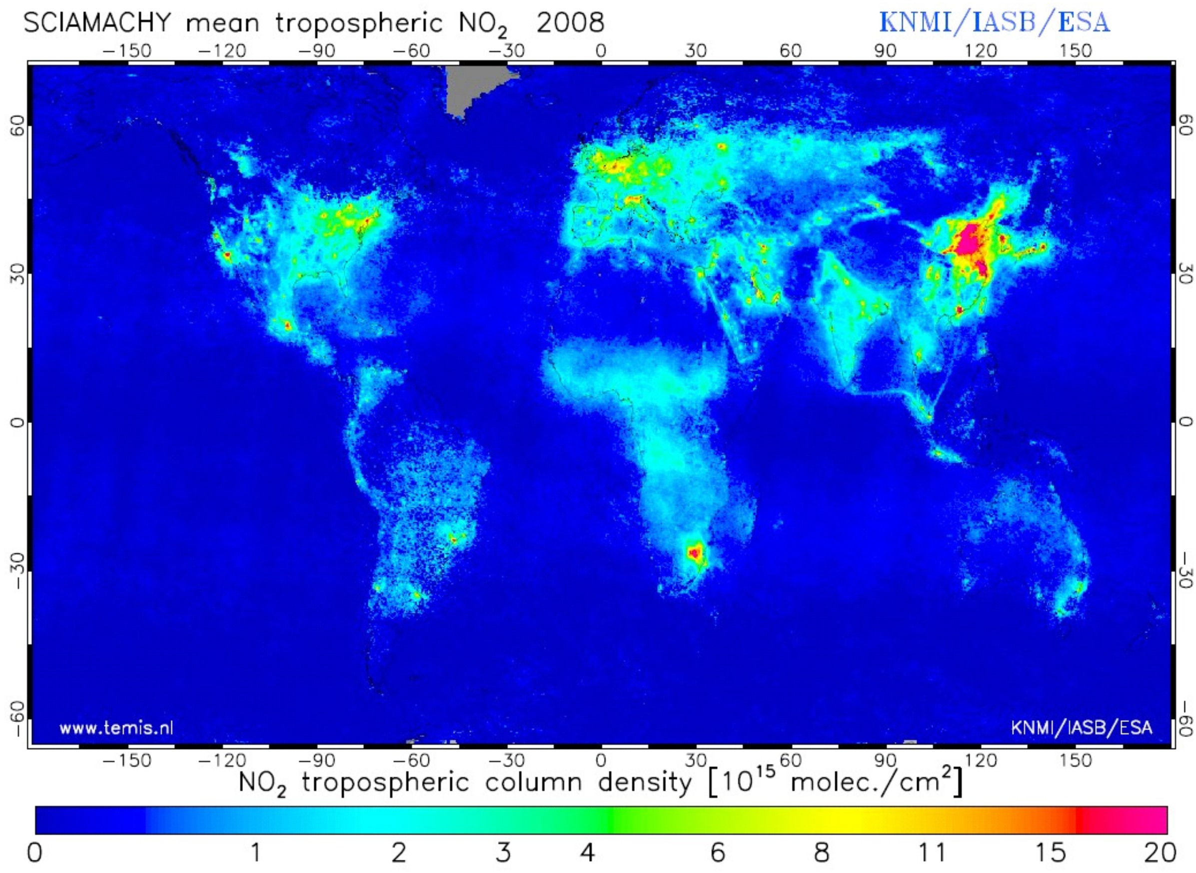
Pollution is the introduction of contaminants into an environment that causes instability, disorder, harm, or discomfort to the ecosystem, i.e. physical systems or living organisms. Pollution can take the form of chemical substances, or energy, such as noise, heat, or light energy. Pollutants, the elements of pollution, can be foreign substances or energies, man-made or naturally occurring; when naturally occurring, they are considered contaminants when they exceed natural levels. Many pollutants can be observed, monitored, and tracked from space.

6.1.4.1 Atmospheric pollution

Many atmospheric gases can be observed from space. Polluting gases, such as SO_2, NO_2, ozone and other gases, can be seen and tracked (see Fig. 6-3), and their concentration monitored.

FIGURE 6-3

Tropospheric NO_2 observed by the sciamachy instrument on ENVISAT in 2008



EESS.6-03

URL: http://esamultimedia.esa.int/images/EarthObservation/no2scia_world2006_H.jpg

6.1.4.2 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 affected area can be monitored and tracked by satellite. Additionally, data from wind scatterometers and ocean surface slope information can be used to generate information on wind and gravity driven currents which are part of the advective nature of surface oil movement. Satellite-based thermal information can be added to produce initial estimates of vertical motion in the water column.

Natural oceanic pollution in the form of a "red tide" can be detected and monitored from space by observing ocean colour. Red tide is a common name for an algal bloom, associated with the production of natural toxins, depletion of dissolved oxygen, or other harmful conditions. Identifying and quarantining areas afflicted by a red tide protect human health.

Other pollution forms (e.g., chemical water pollutants, coastal sediments resulting from floods) can be detected using satellite images in the visible and/or infra-red spectrum.

6.1.4.3 Land pollution

Land pollution usually takes the form of unwanted pollutants spreading over land areas (e.g., tailings from mining operations) or washing into and polluting rivers. These pollutants may be tracked using multi-spectral spaceborne imagers. Another form of land-based pollution is the thermal pollution of rivers from power plants and other sources. These too can be monitored from space, as can the thermal signatures of cities.

6.1.5 Radio frequency bands used to support disaster management

The frequencies used by the meteorological-satellite and Earth exploration-satellite services for disaster management and relief are summarized in Table 6-1. It is essential that the frequencies allocated to these services remain free of interference.

TABLE 6-1

Frequency bands used to support disaster management

Band (GHz)	**0.43**	**1.25**	**1.42**	**2.65**	**4.90**	**5.30**	**6.70**	**7.15**	**8.60**	**9.60**	**10.65**	**13.50**	**15.40**	**17.25**	**18.70**	**21.30**	**22.30**	**23.80**	**24.10**	**31.50**	**35.55**	**36.50**	**50.30**	**55.00**	**78.50**	**89.00**	**94.00**	**101.0**	**118.0**	**150.5**	**166.0**	**175.5**	**183.0**	**201.0**
Allocation*	A	A	P	p	p	A	p	p	A	A	P	A	P	A	P	P	P	P	A	P	A	P	P	P	A	P	A	P	P	P	P	P	P	P
Coastal hazards & tsunamis	X	X				X					X		X		X	X	X	X		X		X	X	X					X	X	X	X	X	X
Drought	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X				X	X	X	X	X	X	X
Earthquake	X	X				X			X	X																								
Extreme weather									X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X
Floods	X	X	X	X		X			X	X	X	X	X		X	X	X	X	X	X	X	X	X	X		X			X	X	X	X	X	X
Landslides	X	X	X	X		X			X	X	X	X	X		X	X	X	X	X	X	X	X	X	X		X			X	X	X	X	X	X
Pollution (ocean)		X				X																												
Sea & lake ice		X				X		X	X	X	X	X				X				X		X				X								
Volcanoes	X	X				X																												
Wildfires	X		X	X		X			X	X		X		X																				

* NOTE: A = active primary allocation; a = active secondary allocation; P = passive primary allocation; p = passive secondary allocation.

6.2 Benefits related to natural systems

Benefits related to natural systems encompass biology (i.e., ecosystems and biodiversity), geology, hydrology, and meteorology, including climate change.

6.2.1 Ecosystems and biodiversity

Globally, ecosystems are under stress from changes in land-use, air and land 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 (all derived from multi-spectral images) and combining them with topography, land usage, geology, soil data, and climate data.

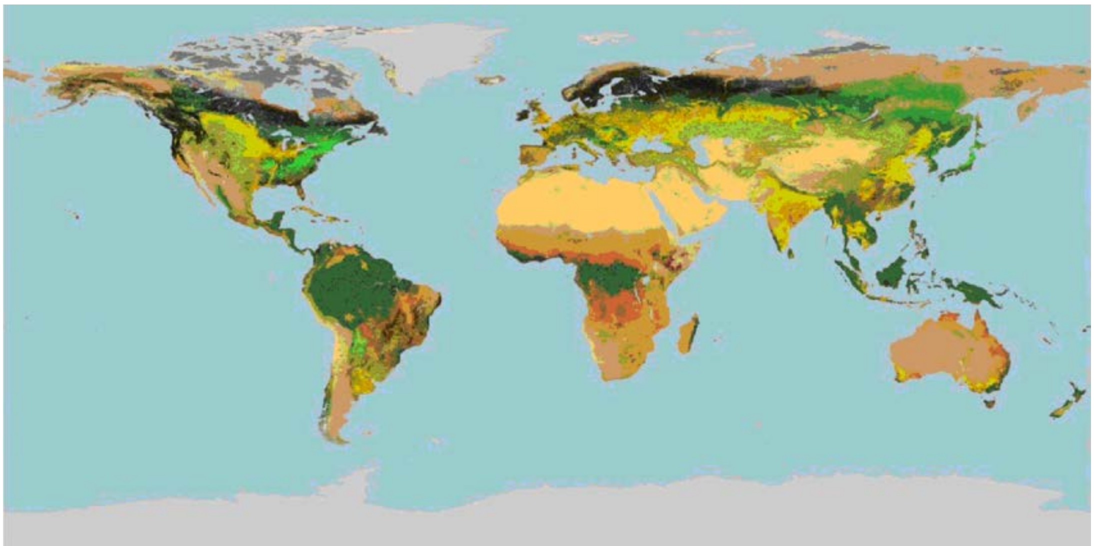
One important field of study is called "land use/land change" and is supported both by multi-spectral visual/infrared imagery (both with moderate and hyperspectral capabilities) as well as by SAR imagery and other satellite-borne remote sensing techniques. Satellite imagery is unsurpassed in this area as a provider of data with consistent, repetitive, global coverage.

Monitoring land use (see Fig. 6-4) and its change includes observing the ecological impacts of agriculture (both land and sea, § 6.4.1), urbanization (the growth and decay of cities, § 6.3.3), desertification (the conversion of farmland into desert, § 6.2.2), deforestation/reforestation (the harvesting and re-growth of forest and woodland), and changes in wetlands and coastal areas.

Some effects of resource overexploitation (e.g., deforestation, large-scale surface mining) can also be observed from space using visual/infrared imagery and SAR imagery. The recovery from such overexploitation can also be monitored.

FIGURE 6-4

Satellite-derived land usage derived from the MODIS instrument flown on Terra



EESS.6-04

URL: http://earthobservatory.nasa.gov/Newsroom/view.php?id=22585

While measuring and monitoring species is generally impractical from space-based platforms, biodiversity data from other sources 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 (see Fig. 6-4). 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 (§ 6.4.5).

6.2.2 Geology

The first and most important direct geologic application of orbital remote sensing has been the study of crustal structure, both regional (tectonic) and local (structural geology). Satellites have been effective in determining the slow but continual movement of the Earth's plates, thus helping to understanding crustal dynamics and associated deformation. Space imagery is well-suited for recognizing and interpreting the types of distortions of layered strata that produce such geologic structures as folds, faults, and fracture sets (joints).

Remote sensing has provided significant benefits to petroleum exploration (see § 6.4.4).

The field of volcanology has benefited enormously from remote sensing. The first comprehensive catalogue of all of the Earth's volcanoes was completed in the 1980s after Landsat imagery produced, for the first time, accurate mapping of remote areas of the Himalaya and Andes mountains. Spaceborne remote sensing can be critical to saving lives in the time around an eruption (see § 6.1.3.3).

Glacial geologists were among the first to make extensive and systematic use of orbital remote sensing data, which provided unique global repetitive coverage, particularly of polar regions. Glacier retreat, or shrinkage, is a strong indicator of global warming and is well monitored from space. Not only are the areas covered by glaciers monitored, but the velocity of the ice flows can also be monitored in situ with the use of RNSS units and remotely through the use of interferometric SARs.

"Aeolian geology" covers the study of wind-dependent processes and the deposits and landforms produced by wind and is roughly equivalent to desert geology. The study of global "sand seas" has been revolutionized by orbital remote sensing. A closely related topic is desertification, the destruction of arid or semi-arid environments by human activity, aggravated in some areas by natural conditions. It has been estimated that 35% of the Earth's land area is in danger of desertification. Orbital remote sensing has been recognized as a valuable tool in monitoring desertification since the earliest days of Landsat. Meteorological satellites have contributed to the study of desertification through the use of multi-spectral visible/infrared and passive microwave systems to map vegetation distribution.

6.2.3 Surface water: hydrology and oceanography

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 and in turn enables forecasts of water supplies. Observed rainfall and weather predictions also provide useful input to water resource managers.

Changes in global and local hydrology, including soil moisture, river and lake levels, etc., can also be followed and their ramifications discovered. The most dramatic short-term event is clearly flooding, which is covered in § 6.1.2.4.

Satellites also aid oceanographic studies, sometimes with far reaching effects. Tracking the occurrence of El Niño/La Niña in the Pacific Ocean using satellite observations allows regional long-term forecasts of weather, including rainfall, and drought conditions (see § 6.1.2.1). Aside from sea ice tracking (see § 6.1.1), sea surface temperatures (both via passive microwave observations), heights (via satellite altimetry), and wind directions and velocities (via satellite-borne scatterometers) are routinely monitored, with current and upcoming missions measuring sea surface salinity.

6.2.4 Weather and climate

Weather monitoring and prediction is the most operationally advanced discipline in the field of Earth observation. For decades, satellite observations have been providing key data leading to improved weather forecasts. These range for tracking cloud motions to providing the temperature and humidity profiles being fed into more and more accurate computer-based weather forecast models. The impact of improved weather forecasts ranges across many human endeavours-agriculture, transportation, water management, public health, construction, tourism/recreation, energy, and others. Extreme weather conditions, such as cyclones, are discussed in § 6.1.2.3.

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 still provide many essential climate variables, some of which are largely dependent upon satellite observations while others are supported or enhanced by satellite observations (see Table 6-2).

In addition, EESS satellites also serve to monitor global effects of climatic changes as they occur. Such effects include the long-term monitoring of sea level and glacial ice and changes in the growing season.

TABLE 6-2

Essential climate variables supplied by satellites

	Atmospheric variables	Oceanic variables	Terrestrial variables
Dependent	Surface Precipitation	Sea surface temperature	Lake levels
	Upper air Earth radiation budget	Sea level	Snow cover
	Upper air temperature	Sea state	Glaciers and ice caps
	Upper air wind speed and direction	Sea ice	Albedo
	Upper air water vapour	Ocean colour (biology)	Land cover (including vegetation type)
	Upper air cloud properties	Sub-surface salinity	Soil moisture
	Carbon dioxide		Leaf area index
	Ozone		Biomass
	Aerosol properties		Fire disturbance
			Fraction of absorbed photosynthetically active radiation
Supported	Surface air temperature	Surface salinity	River discharge
	Surface air pressure	Surface currents	Water use
	Surface radiation budget	Surface CO2 partial pressure	Ground water
	Surface wind speed and direction	Sub-surface temperature	Permafrost/seasonally-frozen ground
	Surface water vapour	Sub-surface currents	
	Methane	Sub-surface nutrients	
	Other long-lived greenhouse gases	Sub-surface carbon	
		Sub-surface ocean tracers	
		Sub-surface phytoplankton	

6.3 Benefits related to humanity

Benefits related to humanity encompass elements of human history (archaeology), human condition (health), and human distribution (population and urban studies).

6.3.1 Archaeology

Aiding archaeologists, satellite-borne remote sensing provides critical insights into the nature of past landscapes. Orbital radar and Landsat images helped discover the hollow ways of Iraq and the complex of buried valleys and drainage channels in the Eastern Sahara and Arabian Peninsula. These tools also helped archaeologists find the ancient city of Ubar in the southern Empty Quarter of the Arabian Peninsula in Oman. They also helped archaeologists find a previously unknown section of the ancient city of Angkor in Cambodia (see Fig. 6-5). Now largely hidden beneath dense jungle growth, Angkor once housed more than a million people. Radar data are being used by archaeologists to understand how the city grew, flourished and later fell into disuse over an 800-year period. The data are also being used to help reconstruct the vast system of hydrological works, canals and reservoirs, which have gone out of use over time.

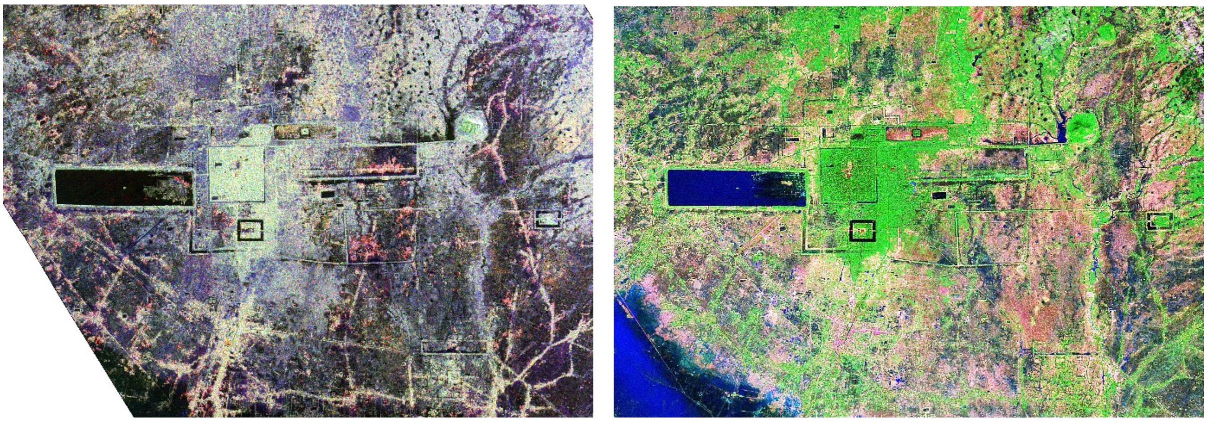
6.3.2 Health

Environmental changes can affect human health. Sudden and severe changes, such as disasters (see § 6.1), are dramatic, although less fast-acting changes also have bad effects. Droughts lead to malnutrition; dust storms, smog, and pollutants in the atmosphere cause respiratory illnesses; contamination of the food supply such as by algae blooms infecting seafood cause illnesses; and some infectious diseases are linked to vectors which thrive in certain environmental conditions. By monitoring the environment on a global scale, the EESS can provide indicators which in turn forecast conditions which threaten human health.

While some pathological conditions (e.g., algae blooms, or red tide) can be directly observed from space platforms, others are traceable to environmental conditions, such as pollutants, which themselves are observable from space.

FIGURE 6-5

Angkor Wat observed by Shuttle Imaging Radar (left) and Landsat 7 (right)



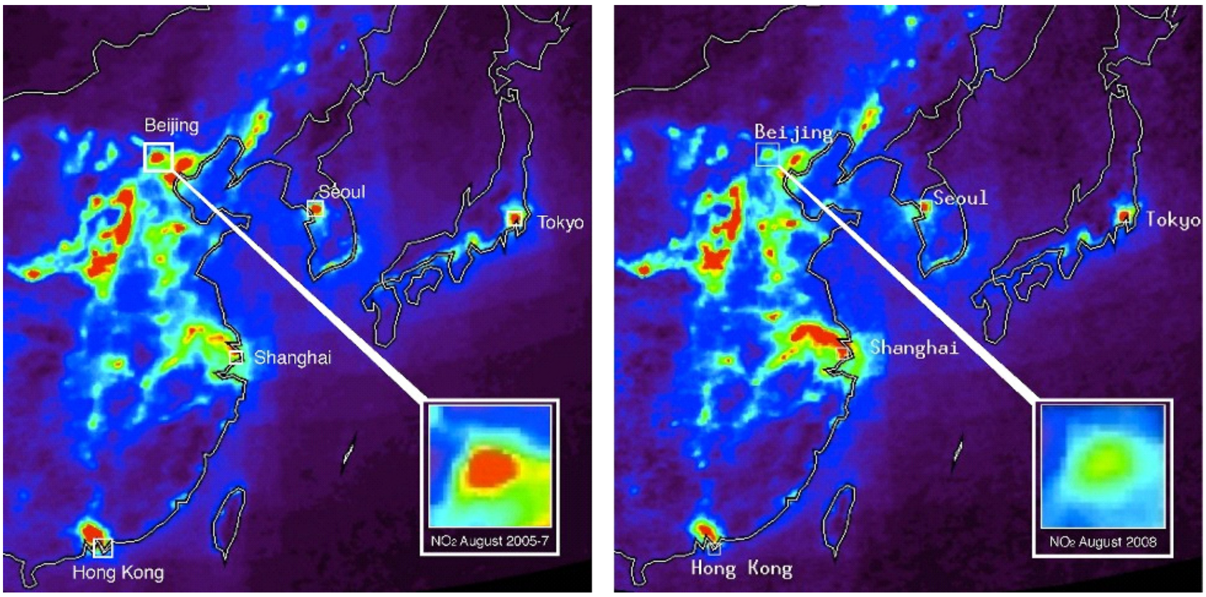
EESS.6-05

Shuttle Imaging Radar Image URL: http://southport.jpl.nasa.gov/sir-c/
Landsat 7 Image URL: https://zulu.ssc.nasa.gov/mrsid/

Sensors are being developed, and some are in use, which monitor specific chemical pollutants. One example is the ability to monitor nitrogen dioxide (NO_2) – a noxious gas primarily resulting from fossil fuel combustion in cars, trucks, and power plants. Satellite observations showed that the levels of nitrogen dioxide plunged nearly 50% in and around Beijing in August 2008 after officials instituted strict traffic restrictions in preparation for the Olympic Games (see Fig. 6-6). Likewise, levels of carbon monoxide fell about 20% over China before and during the 2008 Olympic Games.

FIGURE 6-6

NO_2 level reduction during the Beijing Olympics



EESS.6-06

Data are from the “Ozone Monitoring Instrument” (OMI) on Aura and the “Measurement of Pollution in the Troposphere” (MOPITT) instrument on Terra.
URL: http://www.nasa.gov/topics/earth/features/olympic_pollution.html

6.3.3 Population and urban studies

Population distributions have been mapped using night-time lighting from population centres (see Fig. 6-7) and using road networks, slopes, and land cover as corollary data, most observable from space. As most of the Earth's human population now lives in urban areas (towns and cities), the effects of urbanization upon the global environment need to be monitored and understood.

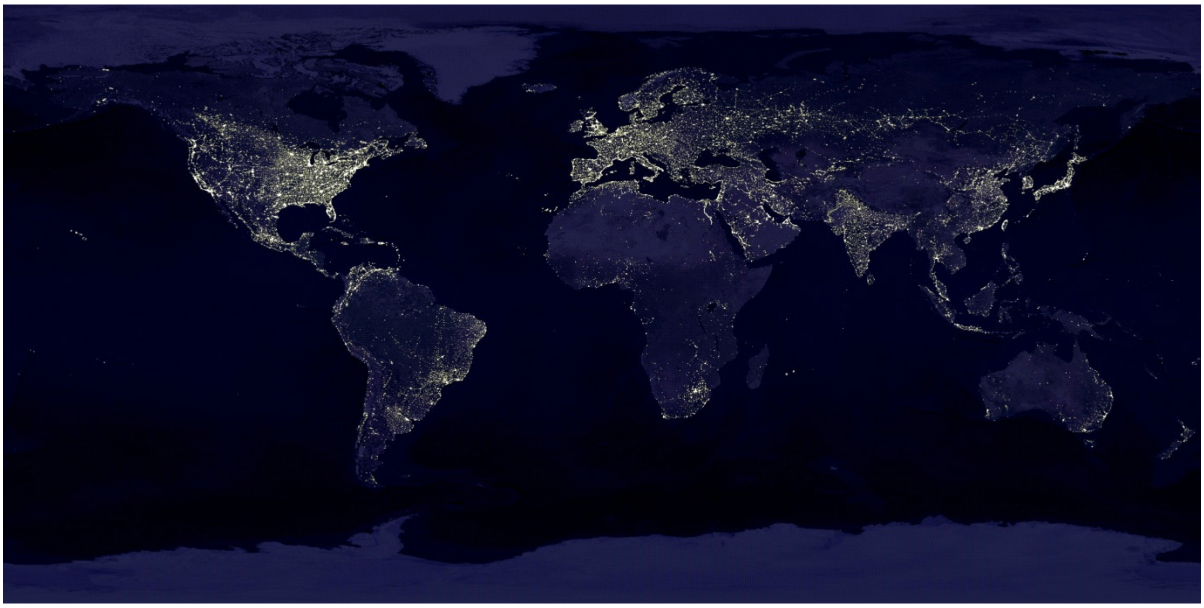
Urban areas can be identified and characterized from space. The extent of urban development worldwide can be easily monitored from space. The growth of cities can be monitored, and the impacts of such growth can be predicted and planned using ecological data regarding the surrounding area.

Similarly, the evolution of cities can be monitored by observing the changes in land use within urban areas. Urban impacts include replacing rain-absorbing soils with impermeable surfaces (e.g., roads, roofs, sidewalks, parking lots, etc.) which affect rain runoff and exacerbate flooding.

The energy, water, food, and other requirements of urban areas place a load on the surrounding ecosystems. Thus the impact of cities also requires monitoring the surrounding areas and their urban-induced changes – such as augmented transportation networks (roads and rails) and added infrastructure such as power lines, airports, reservoirs, etc. EESS data can provide a basis for planning ecologically sound urban expansion.

FIGURE 6-7

Visible night lights on the earth observed from space by the USA's DMSP satellites



EESS.6-07

URL: http://visibleearth.nasa.gov/view_rec.php?id=1438

6.4 Benefits related to human endeavours

Benefits related to human endeavours encompass the areas where humanity makes use of the Earth: agriculture (raising food), cartography (mapping the Earth), communications, energy and resource exploration, and transportation.

6.4.1 Agriculture

The most obvious agricultural use of EESS (particularly, meteorological satellites) is in improving weather forecasts (see § 6.2.4) which help farmers plan their seeding and harvest operations. Further, satellite observations support drought predictions, sometimes far enough in advance for farmers to plan accordingly (see § 6.1.2.1).

Satellite imagery is used to monitor crop health on a global scale by observing leaf indices, vegetation indices (both via multi-spectral imagery), rainfall, and soil moisture. The onset of crop failures leading to famines can be monitored and appropriate resources brought to help. On occasion, satellite observations have located a nearby bumper crop which led to timelier and less costly relief operations.

The advent of satellite observations and precision location systems has led to the development of "precision farming", which permits maximizing agricultural output while minimizing the use of pesticides, fertilizers, and irrigation to only those areas which truly need them.

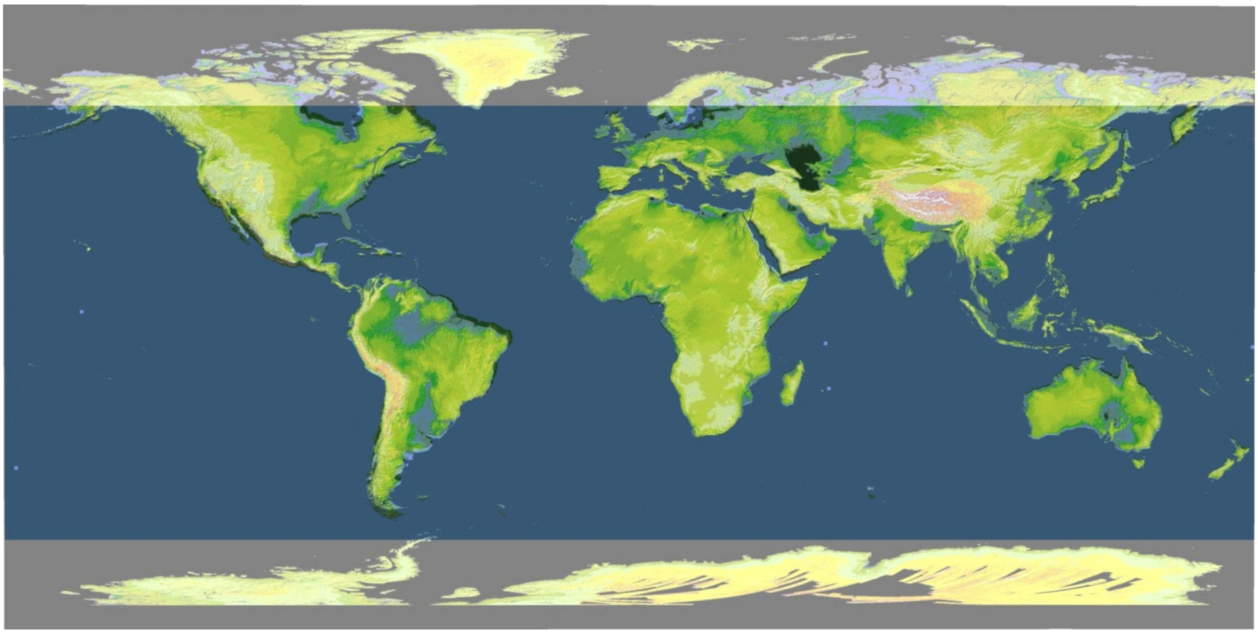
6.4.2 Cartography

There are many cartographic (mapping) uses of orbital remote sensing. One cartographic use is the almost immediate mapping of damage following a disaster (see § 6.1). Radar, in particular, is useful in piercing through cloud cover and identifying, for example, which areas are flooded and which roads are still passable. Visible imagery is also extremely useful in aiding disaster response and recovery, but can be obscured by cloud cover.

The Shuttle Radar Topology Mission (SRTM) provided the first topological mapping of most the Earth's land surface, roughly between +/– 60 degrees of latitude. This data set was made publicly available at a resolution of 90 m. Later, a new data set based on topology derived from the ASTER instrument flown on the TERRA mission provided world-wide coverage between +/– 83 degrees of latitude at a resolution of 30 m (see Fig. 6-8). Both data sets covered areas previously either poorly mapped or not mapped at all in three dimensions. Unfortunately, both data sets suffer from not necessarily measuring to the surface of the ground in forested or built-up areas. The SRTM radar penetrated cloud cover and most vegetation. ASTER data is better in cloud free areas of high-relief terrain where the SRTM radar is shadowed or poorly reflected. The lower radar frequencies (around 1-6 GHz) penetrate farther through the vegetation than higher frequencies (e.g., at or above 13 GHz) which are reflected by water and are used primarily to measure rainfall and the ocean surface.

FIGURE 6-8

The topography of the Earth's land masses provided by SRTM data (dark areas only) and ASTER data (entire area, including SRTM areas)



EESS.6-08

URL: http://www.nasa.gov/topics/earth/features/20090629.html (ASTER);
http://www2.jpl.nasa.gov/srtm/world_radar_images.htm (SRTM).

Another benefit is the use of orbital imagery to derive land use/land cover maps over large areas (see § 6.2.1).

6.4.3 Communications

Satellite data are used by communications engineers to plan the location of new cell phone towers by using satellite-derived land change maps to show where the population is growing, and DEMs to provide lines-of-sight.

6.4.4 Energy and resource exploration

Space-based observations are of some use in identifying energy sources. Solar radiation combined with meteorology can be used to identify optimum locations for solar-derived energy installations. EESS capabilities aid prospecting by helping locate oil by finding natural oil seepage using SARs and by helping locate useful mineral deposits from multispectral imagery and DEMs. The most effective use of remote sensing data in the field of petroleum exploration is generally as a means of focusing surface and subsurface surveys through providing structure mapping. Space-acquired data (principally images) supersede previous approaches, which relied on extensive ground and aerial surveys, simply by showing larger, regional tracts of land. After appropriate processing, full scenes (e.g., Landsat scenes covering 34 000 km^2) often reveal much smaller locales that display guides to mineralization or oil/gas deposits, including surface indicators of leaking subsurface oil and gas.

Space-based observations can support energy conservation by providing planning information in the form of monitoring and forecasting water resources (hydropower), surface winds over water (potential wind power systems), weather conditions (affecting most forms of transportation, especially aviation), etc. In addition, weather forecasts help power companies match their supplies to anticipated demands and transportation companies to optimize routing of shipments and equipment.

6.4.5 Transportation

Transportation systems (roads, canals, airports, terminals, ports, etc.) place a burden on the environment beyond simply replacing soil with impermeable materials. Animal migration paths are disrupted, rain runoff flows are changed, and local fauna are threatened with divided, and sometimes isolated, ecosystems. EESS data such as topology, land use/land change maps, soil maps, etc., can provide a basis for planning future transport development in a cost-effective but least-invasive and least-obstructive fashion.

6.5 Radio techniques associated with societal benefits

The EESS provides beneficial data which is useful if not essential to humankind. Specific bands of radio frequencies are used by the EESS to obtain those data. It is essential that the frequencies allocated to these services remain free of interference. Table 6-3 cross references the type of satellite-derived data product and its benefit to society.

TABLE 6-3

Remote sensing products used to benefit society

Technique	Benefit area	Disasters	Natural systems				Humanity			Human endeavours				
			Ecosys./Biodiv.	Geology	Hydro/Oceanography	Weather/Climate	Archeology	Health	Population/Urban	Agriculture	Cartography	Communication	Energy/Resources	Transportation
Passive														
Vis/IR	Air chemistry	X	X			X		X						
	Multi-spec. images	X	X	X	X	X	X	X	X	X	X	X	X	X
	Spectra	X	X	X		X	X	X		X			X	
Microwave	Air chemistry	X	X			X		X						
	Air humidity profile	X	X		X	X		X		X				
	Air temp profile	X	X		X	X		X		X				
	Images	X			X	X								
	Rain/Rain rate	X	X		X	X				X				X
	Sea salinity		X		X									
	Sea surface temp.	X			X	X								
	Snow cover	X	X		X	X				X				X
	Soil moisture	X	X	X	X			X		X				
Active														
LIDAR	Dig. elev. model	X	X	X	X					X	X	X	X	X
RADAR	Clouds	X				X								
	Dig. elev. model	X	X	X	X					X	X	X	X	X
	InSAR	X		X							X			
	Lake height (Alt.)	X	X		X					X				
	Rain/Rain rate	X	X		X	X				X				X
	SAR images	X	X	X	X		X		X	X	X		X	X
	Sea salinity		X		X									
	Sea height (Alt.)	X			X	X								
	Sea winds (Scatt.)	X			X	X							X	X
	Soil moisture	X	X	X	X			X		X				

APPENDIX 1

ITU-R RECOMMENDATIONS RELEVANT TO THE EARTH EXPLORATION-SATELLITE SERVICE

Recommendation ITU-R	Title
RS.515-4	Frequency bands and bandwidths used for satellite passive sensing
RS.577-7	Frequency bands and required bandwidths used for spaceborne active sensors operating in the Earth exploration-satellite (active) and space research (active) services
RS.1028-2	Performance criteria for satellite passive remote sensing
RS.1029-2	Interference criteria for satellite passive remote sensing
RS.1166-4	Performance and interference criteria for active spaceborne sensors
RS.1259	Feasibility of sharing between spaceborne passive sensors and the fixed service from 50 to 60 GHz
RS.1260-1	Feasibility of sharing between active spaceborne sensors and other services in the range 420-470 MHz
RS.1261	Feasibility of sharing between spaceborne cloud radars and other services in the range of 92-95 GHz
RS.1279	Spectrum sharing between spaceborne passive sensors and inter-satellite links in the range 50.2-59.3 GHz
RS.1280	Selection of active spaceborne sensor emission characteristics to mitigate the potential for interference to terrestrial radars operating in frequency bands 1-10 GHz
RS.1281	Protection of stations in the radiolocation service from emissions from active spaceborne sensors in the band 13.4-13.75 GHz
RS.1282	Feasibility of sharing between wind profiler radars and active spaceborne sensors in the vicinity of 1 260 MHz
RS.1347	Feasibility of sharing between radionavigation-satellite service receivers and the Earth exploration-satellite (active) and space research (active) services in the 1 215-1 260 MHz band
RS.1416	Sharing between spaceborne passive sensors and the inter-satellite service operating near 118 and 183 GHz
RS.1449	Feasibility of sharing between the FSS (space-to-Earth) and the Earth exploration-satellite (passive) and space research (passive) services in the band 18.6-18.8 GHz
RS.1624	Sharing between the Earth exploration-satellite (passive) and airborne altimeters in the aeronautical radionavigation service in the band 4 200-4 400 MHz
RS.1628	Sharing in the band 35.5-36 GHz between the Earth exploration-satellite service (active) and space research service (active), and other services allocated in this band
RS.1632	Sharing in the band 5 250-5 350 MHz between the Earth exploration-satellite service (active) and wireless access systems (including Radio local area networks) in the mobile service
RS.1749	Mitigation technique to facilitate the use of the 1 215-1 300 MHz band by the Earth exploration-satellite service (active) and the space research service (active)

Recommendation ITU-R	Title
RS.1803	Technical and operational characteristics for passive sensors in the Earth exploration-satellite (passive) service to facilitate sharing of the 10.6-10.68 GHz and 36-37 GHz bands with the fixed and mobile services
RS.1804	Technical and operational characteristics of Earth exploration-satellite service (EESS) systems operating above 3 000 GHz
RS.1813-1	Reference antenna pattern for passive sensors operating in the Earth exploration-satellite service (passive) to be used in compatibility analyses in the frequency range 1.4-100 GHz
RS.1858	Characterization and assessment of aggregate interference to the Earth exploration-satellite service (passive) sensor operations from multiple sources of man-made emissions
RS.1859	Use of remote sensing systems for data collection to be used in the event of natural disasters and similar emergencies
RS.1861	Typical technical and operational characteristics of Earth exploration-satellite service (passive) systems using allocations between 1.4 and 275 GHz
SA.514-3	Interference criteria for command and data transmission systems operating in the Earth exploration-satellite and meteorological-satellite services
SA.1020	Hypothetical reference system for the Earth exploration-satellite and meteorological-satellite services
SA.1021	Methodology for determining performance objectives for systems in the Earth exploration-satellite and meteorological-satellite services
SA.1022-1	Methodology for determining interference criteria for systems in the Earth exploration-satellite and meteorological-satellite services
SA.1023	Methodology for determining sharing and coordination criteria for systems in the Earth exploration-satellite and meteorological-satellite services
SA.1024-1	Necessary bandwidths and preferred frequency bands for data transmission from Earth exploration satellites (not including meteorological satellites)
SA.1025-3	Performance criteria for space-to-Earth data transmission systems operating in the Earth exploration-satellite and meteorological-satellite services using satellites in low-Earth orbit
SA.1026-4	Aggregate interference criteria for space-to-Earth data transmission systems operating in the Earth exploration-satellite and meteorological-satellite services using satellites in low-Earth orbit
SA.1027-4	Sharing criteria for space-to-Earth data transmission systems in the Earth exploration-satellite and meteorological satellite services using satellites in low-Earth orbit
SA.1154	Provisions to protect the space research (SR), space operations (SO) and Earth exploration-satellite services (EESS) and to facilitate sharing with the mobile service in the 2 025-2 110 MHz and 2 200-2 290 MHz bands
SA.1159-3	Performance criteria for data dissemination, data collection and direct data readout systems in the Earth exploration-satellite service and meteorological-satellite services
SA.1160-2	Interference criteria for data dissemination and direct data readout systems in the Earth exploration-satellite and meteorological-satellite services using satellites in the geostationary orbit
SA.1161-1	Sharing and coordination criteria for data dissemination and direct data readout systems in the Earth exploration-satellite and meteorological-satellite services using satellites in geostationary orbit
SA.1162-2	Performance criteria for service links in data collection and platform location systems in the Earth exploration- and meteorological-satellite services
SA.1163-2	Interference criteria for service links in data collection systems in the Earth exploration-satellite and meteorological-satellite services
SA.1164-2	Sharing and coordination criteria for service links in data collection systems in the Earth exploration-satellite and meteorological-satellite services

Recommendation ITU-R	Title
SA.1258-1	Sharing of the frequency band 401-403 MHz between the meteorological-satellite service, Earth exploration-satellite service and meteorological aids service
SA.1273	Power flux-density levels from the space research, space operation and Earth exploration-satellite services at the surface of the Earth required to protect the fixed service in the bands 2025-2110 MHz and 2200-2290 MHz
SA.1277	Sharing in the 8 025-8 400 MHz frequency band between the Earth exploration-satellite service and the fixed, fixed-satellite, meteorological-satellite and mobile services in Regions 1, 2 and 3
SA.1278 suppressed (CACE/529)	Feasibility of sharing between the Earth exploration-satellite service (space-to-Earth) and the fixed, inter-satellite, and mobile services in the band 25.5-27.0 GHz
SA.1627	Telecommunication requirements and characteristics of EESS and Metsat service systems for data collection and platform location
SA.1810	System design guidelines for Earth exploration-satellites operating in the band 8025-8400 MHz
SA.1862	Guidelines for efficient use of the band 25.5-27.0 GHz by the Earth exploration-satellite service (space-to-Earth) and space research service (space-to-Earth)
S.1339-1	Sharing between spaceborne passive sensors of the Earth exploration-satellite service and inter-satellite links of geostationary-satellite networks in the range 54.25 to 59.3 GHz
F.1247-2	Technical and operational characteristics of systems in the fixed service to facilitate sharing with the space research, space operation and Earth exploration-satellite services operating in the bands 2 025-2 110 MHz and 2 200-2 290 MHz
F.1502	Protection of the fixed service in the frequency band 8 025-8 400 MHz sharing with geostationary-satellite systems of the Earth exploration-satellite service (space-to-Earth)
F.1570-2	Impact of uplink transmission in the fixed service using high altitude platform stations on the Earth exploration-satellite service (passive) in the 31.3-31.8 GHz band
F.1613	Operational and deployment requirements for fixed wireless access systems in the fixed service in Region 3 to ensure the protection of systems in the Earth exploration-satellite service (active) and the space research service (active) in the band 5250-5350 MHz
M.1653	Operational and deployment requirements for wireless access systems including radio local area networks in the mobile service to facilitate sharing between these systems and systems in the Earth exploration-satellite service (active) and the space research service (active) in the band 5470-5570 MHz within the 5460-5725 MHz range
M.1747	Protection of the Earth exploration-satellite service (passive) in the band 1 400-1 427 MHz from unwanted emissions of mobile satellite service feeder links that may operate in the bands 1390-1392 MHz (Earth-to-space) and 1430-1432 MHz (space-to-Earth)

ISBN 978-92-61-18961-7

Printed in Switzerland
Geneva, 2011

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