ITU ACTIVITY FOR SPACE SCIENCE SERVICES

Dr. Vadim Nozdrin, Study Group Counsellor

Study Group Department, Radiocommunication Bureau, ITU, Geneva, Switzerland

Introduction

This background paper provides basic definitions, sheds light on the technical principles underlying the operation and compatibility of science service systems and presents their main applications.

Definitions

The category of space science services includes the following services [2]:

– *standard frequency and time signal service (SFTSS):* A radiocommunication service for scientific, technical and other purposes, providing the transmission of specified frequencies, time signals, or both, of stated high precision, intended for general reception.

– *standard frequency and time signal-satellite service (SFTSSS):* A radiocommunication service using space stations on earth satellites for the same purposes as those of the standard frequency and time signal service.

– *Earth exploration-satellite service (EESS):* A radiocommunication service between earth stations and one or more space stations, which may include links between space stations, in which:

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

  – similar information is collected from airborne or Earth-based platforms;

  – such information may be distributed to earth stations within the system concerned;

  – platform interrogation may be included.

This service may also include feeder links necessary for its operation.

– *meteorological-satellite service (METSAT):* An earth exploration-satellite service for meteorological purposes.

– *space operation service (SOS):* A radiocommunication service concerned exclusively with the operation of spacecraft, in particular space tracking, space telemetry and space telecommand.

These functions will normally be provided within the service in which the space station is operating.

– *space research service (SRS):* A radiocommunication service in which spacecraft or other objects in space are used for scientific or technological research purposes.

– *radio astronomy service (RAS):* A service involving the use of radio astronomy.

In addition, it may be useful to give the definitions of the following terms which are used often in describing the operation of science services:

– *deep space:* Space at distances from the Earth equal to, or greater than, 2×10^6 km.

– *active sensor:* A measuring instrument in the earth exploration-satellite service or in the space research service by means of which information is obtained by transmission and reception of radio waves.

– *passive sensor:* A measuring instrument in the earth exploration-satellite service or in the space research service by means of which information is obtained by reception of radio waves of natural origin.

Standard frequency and time signal services

ITU is an international organization that plays an important role in the standardization and global distribution of standard frequency and precise time signals. As is well known, any event can be defined by three spatial coordinates and one time coordinate. Clearly, time has to be defined in a standard way and synchronized worldwide with extreme accuracy. One of the basic accepted concepts is that a timescale is an ordered and correspondingly numbered collection of points on a scale. Today, four timescales are used to a greater or lesser degree:

– Universal time (UT1)

– Ephemeris time (ET)

– International atomic time (TAI)

– Coordinated universal time (UTC)

UT1 is a time determined from observation of the Earth's rotation. It is proportional to the rotation angle of the Earth on its axis. The coefficient of proportionality is selected so that 24 hours UT1 is close to the average duration of a day and the phase is determined such that zero hours UT1 corresponds to mean midnight in Greenwich. A UT1 second is understood as a 1/86400th part of the average solar day. A UT1 second was one second in the international system of units (SI) until 1960, and UT1 was the reference timescale until 1972. It is calculated and supported by the International Earth Rotation Service (IERS).

Astronomers have proven that a tropical year offers greater stability of time intervals than a day. A tropical year is understood as the interval between two consecutive passages of the sun through the vernal equinox. In other words, time is maintained more accurately by using the Earth's orbital movement around the sun than by using the Earth's rotation. ET is determined using the value of the Sun's mean longitude. It was selected so that UT1 and ET approximately coincided in 1900. A second of ET is determined as 1/31556925.9747th of a tropical year for the year 1900 on 0 January at 12 hours ET. It was used as the SI unit from 1960 to 1967.

Unlike the above two timescales, TAI is determined on the basis of calculation of a time interval determined from a physical phenomenon. TAI is the coordinate time standard set by the International Time Bureau (BIH) on the basis of the time kept by atomic clocks working in various laboratories engaged in determining an SI second. The atomic second has been the SI unit of time since 1967. It is defined as follows: A second is the duration of 9 192 637 770 periods of radiation corresponding to the transition between two hyperfine levels of the basic structure of a caesium-133 atom. The starting point for counting TAI time was officially agreed so as to coincide with UT1 on 1 January 1958. Atomic time is determined by the Time Section of the International Bureau of Weights and Measures (BIPM), which collects and processes the times kept by around 400 atomic clocks located in 45 countries.

The idea of unifying the different timescales in order to increase accuracy led to the adoption, as from 1972, of UTC as the standard time. UTC is determined by the following system of equations:

$$\mathrm{UTC(t)} - \mathrm{TAI(t)} = \mathrm{n\ s}\ (\text{where n is a whole number, currently n} = 34\ \mathrm{s})$$

$$|\mathrm{UTC(t)} - \mathrm{UT1(t)} < 0.9\ \mathrm{s}|$$

ITU-R recommends that all standard-frequency and time-signal emissions conform to UTC [3]. It should be noted that the Earth's rotation speed may vary, resulting in a divergence between UT1 and TAI. In such cases, IERS may take the decision to regulate the second in relation to the predicted deviation between the timescales. Leap seconds are added or subtracted at the end of a month.

The UTC standard timescale is calculated and distributed by BIPM. At the same time, users worldwide have access to local UTC values through local laboratories (UTC(k)), of which there are now some 60 worldwide. They are coordinated both with UTC and among themselves. The maximum deviation between UTC and UTC(k) shall not exceed ±1 millisecond, while ITU-R recommends ±100 nanoseconds [4]. UTC(k) provides reference standards for distribution in the territories concerned by means of various systems, in particular broadcasting in SFTSS and SFTSSS, the broadcasting-satellite service, the fixed-satellite service, the radionavigation-satellite service and the meteorological-satellite service, and also on terrestrial networks over optical fibre or coaxial cable. The Radio Regulations stipulate that administrations wishing to provide standard frequency and time signals shall closely coordinate their work with those who already have such systems [5].

Until recently, the broadcasting of precise time and standard frequency signals within SFTSS and SFTSSS was a very popular method of disseminating this information. Table 1 shows the frequency bands allocated to these two services in accordance with the Radio Regulations, in addition to which some frequency bands in the range 14-90 kHz can also be used [6]. Terrestrial stations are in use worldwide and offer global coverage, providing the required services with a very high quality (accuracy of up to 10^{-12}). They are, however, now gradually being supplanted by satellite technologies.

TABLE 1

Bands allocated to SFTSS and SFTSSS

SFTSS	SFTSSS
20.0 ± 0.05 kHz	400.1 MHz ± 25 kHz
2.5 ± 0.005 MHz	4 202 MHz ± 2 MHz (space-to-Earth)
5.0 ± 0.005 MHz	6 427 MHz ± 2 MHz (Earth-to-space)
10.0 ± 0.005 MHz	13.4-14 GHz (Earth-to-space)
15.0 ± 0.01 MHz	20.2-21.2 GHz (space-to-Earth)
20.0 ± 0.01 MHz	25.25-27 GHz (Earth-to-space)
25.0 ± 0.01 MHz	30-31.3 GHz (space-to-Earth)

The most forward-looking technology supporting the standard frequency and time signal service with a very high degree of accuracy is the satellite. Systems are in use today that operate in the radionavigation-satellite service (RNSS). The frequency bands allocated to the RNSS are shown in Table 2. There are two global satellite groupings – GPS and GLONASS – forming the Global Navigation Satellite System (GNSS). In addition, three regional systems are in use, specifically the Wide Area Augmentation System (WAAS), covering the United States, the European Geostationary Navigation Overlay Service (EGNOS), providing radionavigation services in Europe, and the Multi-functional Satellite Augmentation System (MSAS), accessible in Japan and neighbouring countries. The regional systems use GPS signals as a basis and enhance the quality of service using signals from other satellites.

TABLE 2

RNSS and RNS frequency bands used to transmit standard time signals

RNSS	RNS
1 164-1 215 MHz (Earth-to-space, space to-Earth) 1 215-1 300 MHz (space-to-Earth, space-to-space) 1 559-1 610 MHz (space-to-Earth, space-to-space) 5 000-5 010 MHz (Earth-to-space) 5 010-5 030 MHz (Earth-to-space, space-to-Earth)	9-14 kHz 90-110 kHz

In some instances, navigational signals are transmitted by other satellite systems, belonging to the fixed-satellite, the meteorological-satellite or the broadcasting-satellite service. In particular, time signals are transmitted from the GOES meteorological satellites and the INSAT communications satellite. In view of the wide distribution of RNSS receivers, however, these signals are not used on a massive scale.

The most widely used LF navigation system distributing standard time signals is currently eLoran (Enhanced Long Range Navigation). The system is being developed and is expected to consist of 40 stations worldwide. They will all operate at 100 kHz (Table 2). It is suggested that eLoran may be used as a backup for GNSS, as well as to enhance the accuracy and reliability of the latter's services. Also to be noted is Russia's operational Alpha LF radionavigation system (10-17 kHz).

Accurate standard time and frequency signals are necessary not only for everyday use but are also vital for various industry sectors, with metrology and fundamental and applied physics coming high on the list. The international SI system, in particular, is devised around seven base units, one of which is time and its unit, the second. An unlimited number of desired units can be formed from the base units, such as speed, current strength, heat transfer rate, etc. As an example, the current definition of the metre, as adopted by BIPM, is linked to the definition of a second: "the metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 468 of a second".

A vital application of standard frequency and time signals is radionavigation, insofar as this application ensures the safety of human life when travelling by maritime, air or land transport. The use of radionavigation aids in cars is taking on ever-increasing importance, enhancing travel comfort and safety. The telecommunication sector also has a critical need for such signals in order to synchronize networks, failing which they cannot operate.

Earth exploration-satellite service (EESS)

The EESS includes three categories of subsystem:

– Passive sensors, which are used to study various physical processes through the observation of natural electromagnetic radiation.

– Active sensors, whose operating principle is based on the analysis of electromagnetic waves artificially generated by specific equipment and reflected by the object studied.

– A subsystem performing radiocommunication functions such as the transmission of information in real time to any station (earth station or space station) within the satellite's field of vision, the provision of feeder links between earth stations and satellites for the transmission of collected and stored information and satellite control, and finally the collection and storage of information on specific land-based or aeronautical platforms and its uploading to satellites. In addition, the frequency bands in question are used for satellite telecommand signals.

Every body in nature absorbs a portion of any electromagnetic radiation falling upon it, reflects another portion and, generally speaking, allows yet another portion to pass through it. According to Kirchhoff's Law, the emissivity of a body depends on thermal temperature and frequency. Thus, every body in the atmosphere has unique emissivity characteristics, thanks to which it is possible to identify its presence at a point of observation. By the same token, the absence of radiation at certain frequencies helps to determine the presence in the atmosphere of specific gases, their amount and their distribution.

Since the level of the observed emissions is very low, amounting virtually to thermal noise, atmospheric attenuation can have a huge impact on them, particularly on account of radio-wave energy absorption in oxygen and water vapour in the atmosphere, as can emissions from the Earth's atmosphere itself. In these circumstances, selecting the right frequencies for passive sensors is critical to achieving the required measurement quality, since far from all frequencies are suitable for observations. Figure 1 shows attenuation for frequencies from 0 to 1 000 GHz 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) [7]. The curves show that from the point of view of attenuation, the best frequencies for observation at the Earth's surface are in the range below 100 GHz. The frequency range above 50 GHz is characterized by atmospheric gas absorption lines, and is thus suitable for study of the Earth's atmosphere.

FIGURE 1

Specific attenuation in atmospheric gases

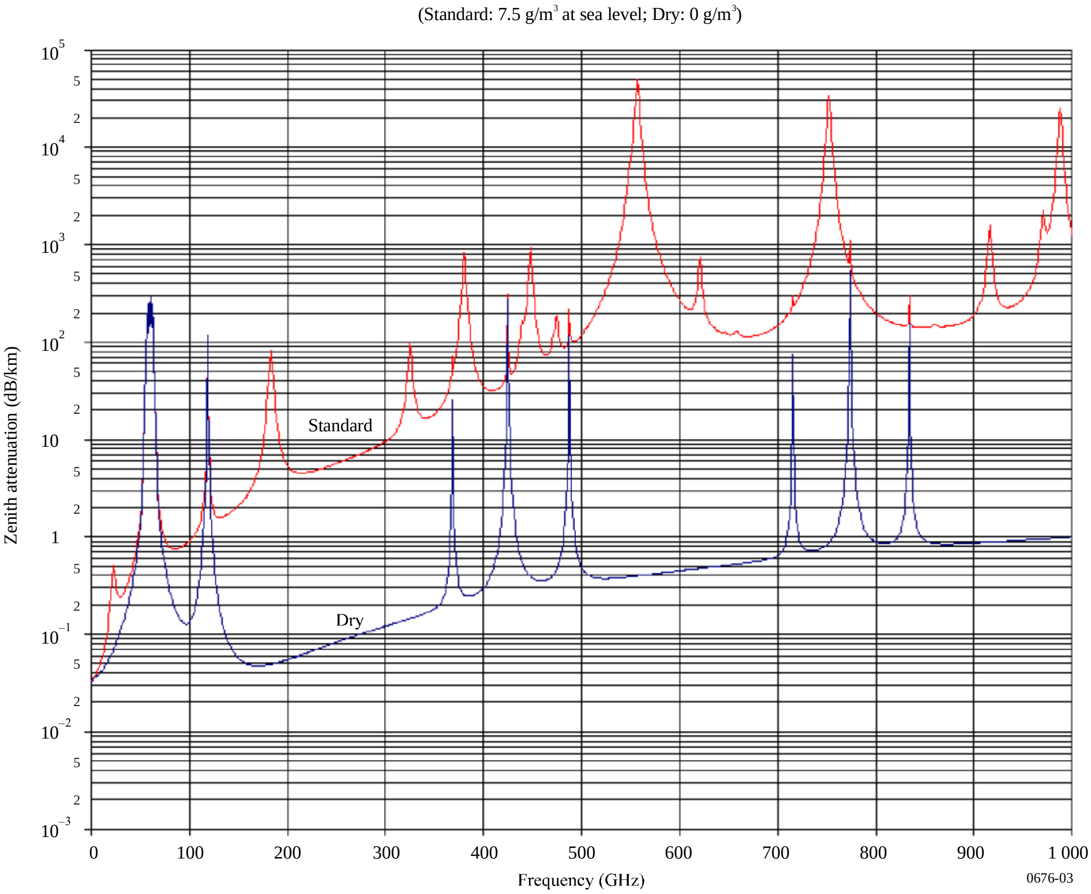


Figure 2 plots the sensitivity of the brightness temperature of sea surface components to frequency. The curves show that the choice of frequency bands for EESS is very restricted, since only certain frequency bands are suitable for observing particular characteristics. Thus, for example, measurements at frequencies around 1.4 GHz provide the most accurate information on salinity, the 6 GHz band is most suitable for measuring sea temperature, 24 GHz for water vapour and above 36 GHz for water clouds.

Figure 3 plots the sensitivity of the brightness temperature of geophysical parameters of the Earth's surface. The chart clearly shows, for example, that soil moisture is most accurately measured in the band below 1 GHz, that the most suitable frequencies for measuring the Earth's vegetation coverage are in the range between 5 and 10 GHz, and that the optimum band for water vapour is 23-24 GHz. Surface roughness of the Earth may be determined with a high degree of quality in the band above 35 GHz. Monitoring of snow-covered regions is important, and identifying a few necessary frequencies is here again crucial. In practice, a distinction needs to be drawn between snow and ice, and also between degrees of freshness of snow. The relevant signals are linked to the structure of snow layers and the dimensions of crystals. To obtain this information, a number of frequencies are required: usually 19 GHz, 37 GHz and 85-90 GHz.

FIGURE 2

Sensitivity of the brightness temperature of sea surface components to frequency

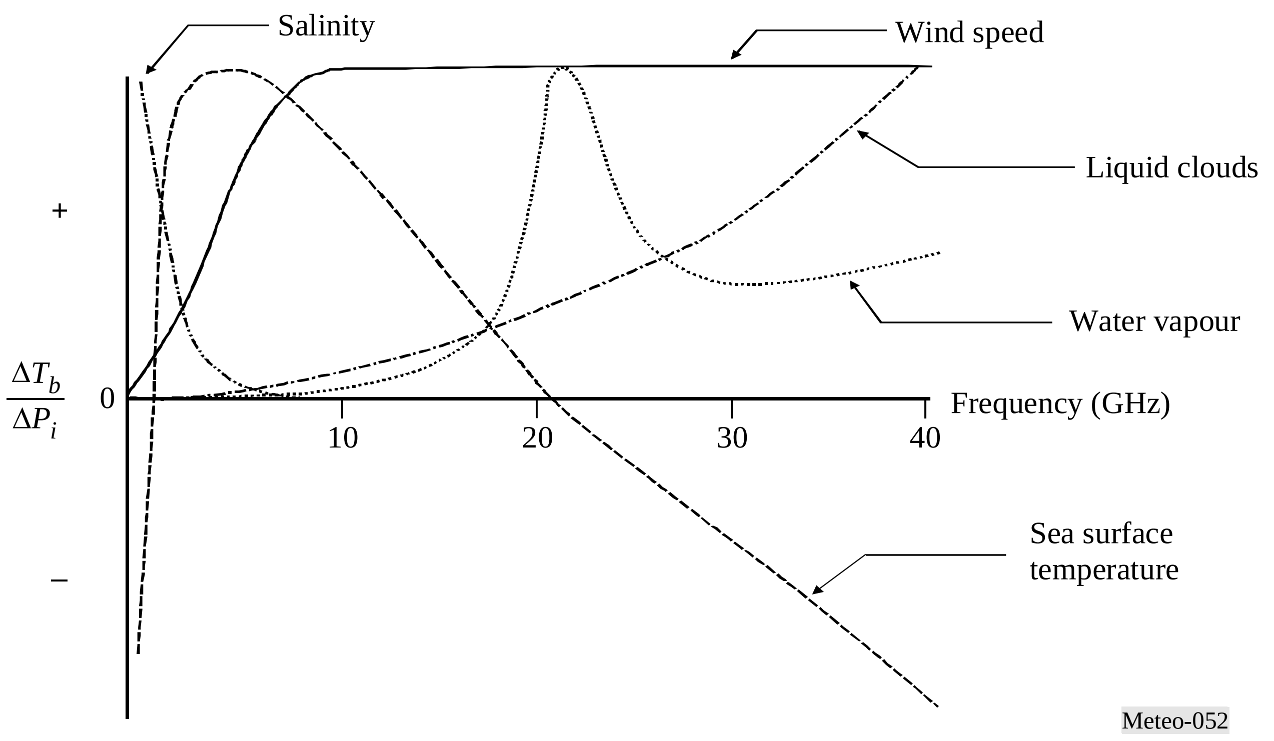
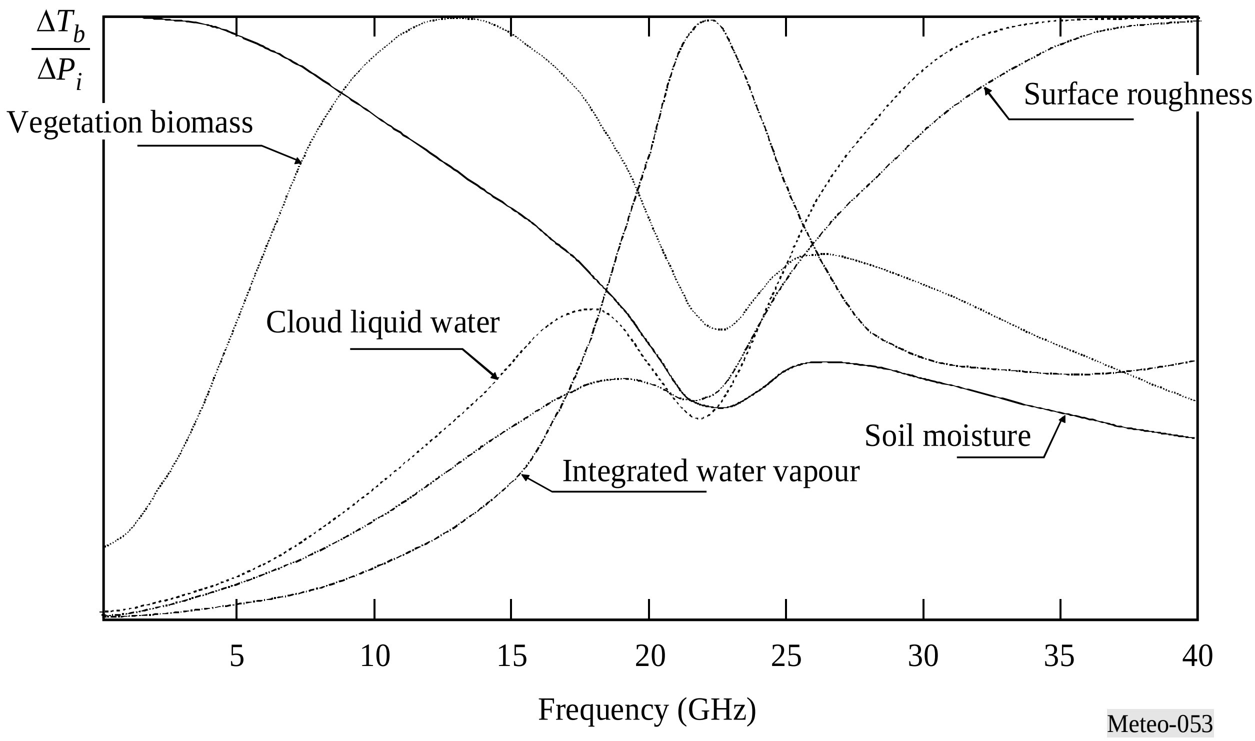


FIGURE 3

Sensitivity of the brightness temperature of components of the Earth's surface to frequency



To normalize the permissible level of interference caused to passive sensors located on board satellites, we apply the threshold value of the radiometer ΔP, in W [8]:

$$\Delta P = k \Delta T_e B_{wr},$$

where:

k: Boltzmann's constant

ΔT_e: radiometric tolerance of the sensor (K)

B_{wr}: reference frequency band of the radiometric channel (Hz).

The maximum level of interference must not exceed 20% of ΔP. It thus becomes clear that, in practice, shared use of frequencies of active services with passive sensors is impossible. In these circumstances, the Radio Regulations identify a series of frequency bands in which emissions are forbidden [9]. These include the frequency bands 1 400-1 427 MHz, 2 690-2 700 MHz, 10.68-10.7 GHz, 15.35-15.4 GHz, 23.6-24 GHz, 31.3-31.5 GHz, 31.5-31.8 GHz, 48.94-49.04 GHz, 50.2-50.4 GHz, 52.6-54.25 GHz, 86-92 GHz, 100-102 GHz, 109.5-111.8 GHz, 114.25-116 GHz, 148.5-151.5 GHz, 164-167 GHz, 182-185 GHz, 190-191.8 GHz, 200-209 GHz, 226-231.5 GHz and 250-252 GHz.

The underlying operating principle of EESS active systems resides in the satellite illuminating the object or surface to be studied and capturing the reflected signal, which can be processed and used as a source of information for analysing various characteristics or phenomena. Active sensors present certain advantages by comparison with passive sensors, in that they display unique sensitivity to a number of fluctuating land/sea/atmosphere parameters (e.g. vegetation humidity and cloud height). Furthermore, with active sensing it is possible, for example, to penetrate through the surface and vegetation, operate in any weather and at any time, achieve high spatial resolution, enhance measurement quality by varying the illumination angle, and operate in a wide spectral range without any dependence on emissions from narrowband phenomena.

There are five basic types of EESS active systems:

– Synthetic aperture radars (SAR). SARs scan the observed surface at 10-55° from the nadir, i.e. the point directly below the satellite. They can be used to obtain images of the Earth's surface and topological maps.
– Altimeters. The sensors of altimeter systems scan in the direction of the nadir, measuring the delay between the emission pulses of the transmitted signal and the received reflected signal. They are used to determine the height of various objects in relation to sea level, and also for precise measurement of the depth of rivers and lakes.
– Scatterometers. A scatterometer radar system transmits microwave pulses and receives the signal reflected back from the surface. The intensity of the returned signal depends on the roughness of the surface. For a sea surface, the unevenness due to waves caused by wind increases with wind speed. To determine wind direction, a scatterometer parabolic reflecting antenna rotates at a precisely regulated speed and emits two separate beams approximately six degrees apart, each consisting of a constant stream of pulses.
– Precipitation radars. Scanning is carried out in directions close to the nadir, measuring the reflection from rain and snow clouds. The measurements make it possible to calculate precipitation intensity and construct three-dimensional precipitation models.
– Cloud-profiling radars (CPR). Scanning at the nadir, CPRs measure the reflection from clouds, making it possible to determine cloud relief around the Earth's surface and construct three-dimensional cloud models.

Since the wanted signal traverses the atmosphere twice, attenuating and scattering, choosing the optimum band is very important when planning EESS systems. The list of frequency bands allocated in accordance with the Radio Regulations to EESS (active) and the required frequency band depending on the type of radar are shown in Table 3. On account of the strong atmospheric attenuation at shorter wavelengths, active sensors usually operate below the oxygen absorption band - 60 GHz. It is also necessary to avoid using frequencies around the water vapour resonance line - 22 GHz. The most suitable band for measuring wind speed is 10-15 GHz, and 14 GHz for altimeters. Low-frequency bands, such as 400 MHz, are good for looking within the Earth's surface and observing subterranean reserves of fresh water or changes in the Earth's crust. To enhance measurement quality, observation is generally carried out on two or more frequencies, with different polarizations and at different angles. The bandwidth requirements for active sensors depend on the type of sensor and required measurement quality. Nevertheless, a bandwidth of 100 MHz would be sufficient in practice for any systems with the exception of altimeters.

A subsystem performing telecommunication and telecommand functions operates within both EESS and SOS. Telecommand signals serve to control the power supply for all the satellite's components, correct orientation of the satellite, flight parameters, etc. The communications system serves to disseminate the data collected both in real time and in respect of stored data. The data may be disseminated either directly to the earth stations or via special data relay satellites (DRS) placed in geostationary orbit.

TABLE 3

Frequency bands allocated to EESS and required bandwidth depending on type of radar

Frequency band allocated under RR Article 5	Required bandwidth				
	Scatterometer	Altimeter	SAR	Precipitation radar	Cloud profiling radar
432-438 MHz			6 MHz		
1 215-1 300 MHz	5-500 kHz		20-85 MHz		
3 100-3 300 MHz		200 MHz	20-200 MHz		
5 250-5 570 MHz	5-500 kHz	320 MHz	20-320 MHz		
8 550-8 650 MHz	5-500 kHz	100 MHz	20-100 MHz		
9 300-9 900 MHz	5-500 kHz	300 MHz	20-600 MHz		
13.25-13.75 GHz	5-500 kHz	500 MHz		0.6-14 MHz	
17.2-17.3 GHz	5-500 kHz			0.6-14 MHz	
24.05-24.25 GHz				0.6-14 MHz	
35.5-36 GHz	5-500 kHz	500 MHz		0.6-14 MHz	
78-79 GHz					0.3-10 MHz
94-94.1 GHz					0.3-10 MHz
133.5-134 GHz					0.3-10 MHz
237.9-238 GHz					0.3-10 MHz

The frequencies used for satellite control and data exchange with Earth are shown in Table 4. Currently, the most commonly used band for command functions is 2 025-2 110 MHz and 2 200-2 290 MHz, since this offers the best propagation characteristics and the satellite receiving antenna is usually non-directional. The most commonly used bands for radiocommunication are 2 200-2 290 MHz, 8 025-8 400 MHz and 25.5-27 MHz [10]. WRC-07 adopted additional allocations for these usages on the grounds that research in the future will call for very high transmission speeds exceeding 150 Mbit/s.

The protection criteria for EESS and SOS depend on the frequency band and sharing scenario, and normalize the level of permissible short-term and long-term interference [11]. They are met through mandatory coordination of EESS and SOS earth stations with terrestrial stations and compliance with stringent ERP limits at the Earth's surface for shared use of frequencies by space and terrestrial systems.

TABLE 4

Spectrum allocations for EESS and SOS

Earth-to-space	space-space	space-to-Earth
401-403 MHz 1 427-1 429 MHz 2 025-2 110 MHz 13.75-14 GHz*	2 025-2 110 MHz 2 200-2 290 MHz 13.75-14 GHz* 25.5-27 GHz	401-402 MHz 460-470 MHz* 1 690-1 710 MHz* 2 200-2 290 MHz

28.5-30.0 GHz 40.0-40.5 GHz		8 025-8 400 MHz 13.75-14 GHz* 25.5-27 GHz 37.5-40 GHz*

* Secondary allocation

The value of the data that can be obtained using EESS systems cannot be overstated. Monitoring of atmospheric gases and changes in ice coverage and sea surfaces help to analyse global warming and climate change and find ways of combating them. Major natural catastrophes can be forecast only on the basis of data obtained from space. Combating forest fires and mitigating the effects of natural catastrophes - all this requires the analysis of images showing the status of the territories to be assisted. Data obtained from satellites often prove critically important for ensuring safety of human life, particularly in the realm of maritime and air transport. What is more, earth observation is nowadays becoming a commercial application, such as, for example, high-resolution photographs of the Earth's surface. In 2009, revenues from this activity reached the USD 1 billion mark. There are now some 100 EESS satellites in operation, and the launch of around 90 new EESS satellites is planned between now and 2019.

Space research service (SRS)

The purpose of the SRS is to investigate outer space using radio systems installed on board manned and unmanned space vehicles. Such research enables us to obtain information on the atmosphere and surface of other planets, gravitational fields and the interplanetary plasma, and also to elucidate the laws of planetary motion by establishing the metrics of the solar system. Space vehicles include stations placed in fixed orbits, such as the International Space Station, and others travelling through the Universe or made to land on the surface of planets for the purposes of research. We should note certain very important trends in the development of SRS, such as very long baseline interferometers (VLBIs) in space. The basic principle of such networks is to observe a given phenomenon simultaneously using a number of identical radio telescopes situated far apart from one another (up to 1000 km). By synchronizing the operation of the telescopes, it is possible to obtain a very high resolving power. When radio interferometers are based on space platforms, the angular resolution that is obtained, i.e. the minimum angle between objects that can be distinguished using the optical system in question, is equivalent to that obtainable using a normal telescope with a diameter greater than the Earth's radius.

The SRS carries out the following basic functions:

– transmission of command and programming data from Earth to space vehicles;
– transmission to Earth of operational telemetry data from space vehicle systems and from scientific instruments, including video data showing images of planets and their satellites;
– measurement of radial distances and velocities needed for navigation of space vehicles and investigation into outer space and regions of space in the vicinity of planets.

Data may be downloaded to Earth directly from the space vehicle or via special data relay satellites placed in geostationary orbit.

Harmful interference affecting SRS systems may lead not only to data loss and a lower transmission quality but also to total loss of the ability to control and navigate a space vehicle. Additional requirements for the protection of such systems arise from the fact that distances to such vehicles may be up to several billion kilometres, which means that the noise temperature of receiving devices must be very low. The basic technical parameters of SRS systems which must be taken into account for the purpose of assessing EMC are set out in Tables 5 and 6.

The effectiveness of the scientific and engineering research tasks carried out with the aid of SRS systems depends to a large extent on the correct choice of bandwidth and operating range. The requisite bandwidth depends on the required data transmission rate, mission type, the space vehicle's technical systems, its data storage capacity and the duration of communication sessions with Earth stations. Table 7 sets out examples of frequency band requirements according to the type of information to be transmitted during the course of deep space research. New ITU Report SA.2191, for example, presents the technical basis for the fact that, for planned missions to the moon and to the Lagrange point (situated 1.5 million km from Earth, where the gravitational forces of the Earth and Moon are balanced), a minimum of 600 MHz of uninterrupted bandwidth is required.

TABLE 5

Technical parameters of SRS earth stations

Earth station			
Parameters	**Missions in Earth orbit**	**Deep space**	**DRS**
Antenna diameter	6-30 m	35-70 m	5-19 m
Noise temperature	150-800 K	16-52 K	160-795 K
EIRP	60 dBW	100 dBW	Up to 100 dBW
Antenna radiation pattern	Recs. ITU-R SA.509 and 1345 Reports ITU-R 2098 and 2166		Rec. ITU-R SA.1414
Protection criteria (acceptable spectral density of interference at receiver input)	–216 dB(W/Hz) in the band 1-20 GHz, –156 dB (W/MHz) in the band 20-30 GHz	–222 dB(W/Hz) in the band 2 GHz, –221 dB(W/Hz) in the band 8 GHz, –220 dB(W/Hz) in the band 13 GHz, –217 dB(W/Hz) in the band 32 GHz	–176 dB(W/Hz) in the band 13.4-14.05 GHz, –176 dB(W/Hz) in the band 10.81-10.86 GHz, –172 dB(W/Hz) in the band 17.7-21.2 GHz

TABLE 6

Technical parameters of SRS space vehicles

Space vehicle			
Parameters	**Missions in Earth orbit**	**Deep space**	**DRS**
Noise temperature	700-1500 K	200-2000 K	525-1305 K
Transmission power	2-10 W	5-23 W	Rec. ITU-R SA.1414
Antenna radiation pattern	Non-directional phased antenna array		Rec. ITU-R S.672
Protection criteria (acceptable spectral density of	–177 dBW/kHz in the band 100 MHz - 30 GHz for 0.1% of the time	–193 dBW/20 Hz in the band around 2 GHz, –190 dBW/20 Hz in the band around 7 GHz,	–176 dB(W/kHz) in the band 13.4-14.05 GHz –176 dB(W/kHz) in the band 10.81-10.86 GHz

interference at receiver input)		–186 dBW/20 Hz in the band around 17 GHz, –183 dBW/20 Hz in the band around 34 GHz	–172 dB(W/kHz) in the band 17.7-21.2 GHz

TABLE 7

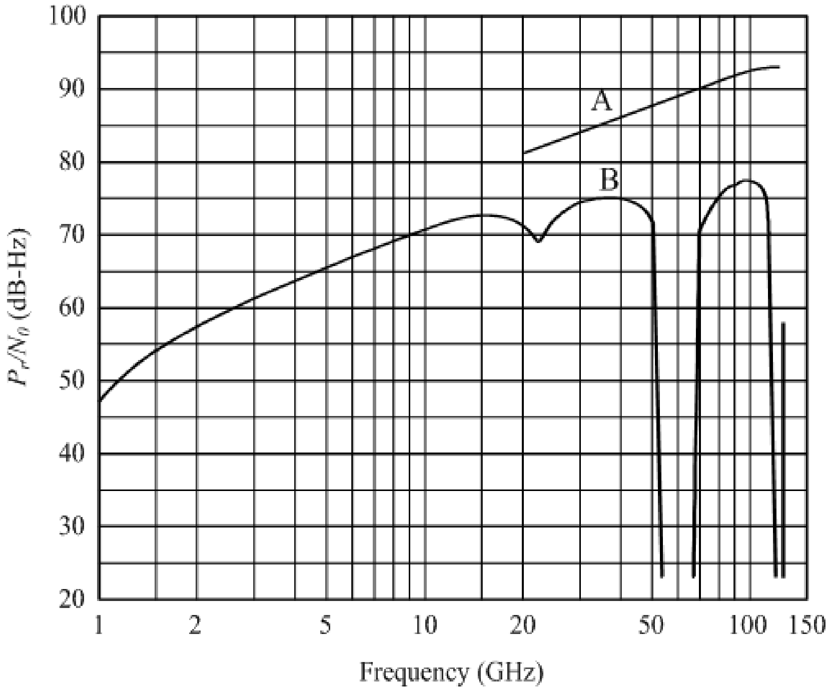
Required frequency bands for SRS

Direction and function	Symbol transmission rate (Msymbol/s)	Bandwidth (MHz)
Earth – space		
Teleguidance	0.002	0.040
Programming	0.2	0.8
Voice transmission	0.045	0.18
Television	30	120
Measurement of motion parameters	100	400
Space – Earth		
Operational telemetry	1.2	4.8
Scientific data	600	1 200
Voice transmission	0.27	1.08
Television	60	240
Measurement of motion parameters	100	400
Operational telemetry	1.2	4.8

The criteria for selecting the optimal radio frequency range for any given mission will vary. Apart from technical characteristics, the criteria also depend on the signal propagation conditions. The best parameter for assessing the efficiency of a radio link is the ratio between the received signal power P_s and the noise spectral power N_0. It should be noted that in computing the link's energy potential, account must be taken not only of the receiver noise, as is the case for most radiocommunication services, but also of the noise temperature associated with space noise having regard to atmospheric and precipitation-related attenuation. The frequency band that ensures the maximum value of P_s/N_0 for any given system characteristics and propagation conditions may be considered optimal. Optimal frequency bands for a particular radio link are determined from the P_s/N_0 frequency dependences. Algorithms for computing atmospheric and precipitation-related attenuation, noise temperature and radio-link efficiency are shown in [11]. By way of an example, Figure 4 shows how the efficiency of a deep space radio link varies with frequency for a frequency range above 20 GHz, calculated for the following characteristics: radio-link length 8×10^8 km, earth station antenna diameter 70 m, earth station transmitter power 100 kW, space vehicle antenna diameter 3.5 m, space vehicle transmitter power 25 W, antenna aperture efficiency 0.6, noise temperature 0 K (ideal receiver). An analysis of the graph shows that the efficiency of radio links passing only through outer space increases with frequency and always exceeds that of radio links passing through the Earth's atmosphere. Nevertheless, radio links that pass through the Earth's atmosphere can be quite efficient in the bands 30-40 GHz and 80-100 GHz. In bands between 60 and 120 GHz, it is possible to establish highly efficient radio links between deep space vehicles and an Earth satellite that are protected from interference originating from other services.

FIGURE 4

Efficiency of deep space – Earth satellite (A) and deep space – Earth station (B) radio links as a function of frequency



Curves:
(A) deep space to satellite
(B) deep space to Earth station

The frequency bands allocated to the SRS in the Radio Regulations and most frequently used in practice are as follows:

– 2 025-2 110 MHz (Earth-to-space, space-to-space), 2 110-2 120 MHz (Earth-to-space), and 2 290-2 300 MHz (space-to-Earth). These bands are used for all-weather radio links with on-board antennas of usually low directivity. The narrow width of these bands limits the data transmission rate and accuracy of distance measurements, especially in the case of communication with two or more space vehicles in a single Earth station antenna beam.
– 7 145-7 235 MHz (Earth-to-space) and 8 400-8 500 MHz (space-to-Earth). These are used for all-weather radio links with high-directivity on-board antennas. They can accommodate fairly high transmission rates.
– 12.75-13.25 GHz (space-to-Earth) and 16.6-17.1 GHz (Earth-to-space). Used for high-directivity on-board antennas in clear weather conditions only.
– 31.8-32.3 GHz (space-to-Earth) and 34.2-34.7 GHz (Earth-to-space). Used for high-directivity on-board antennas, in clear weather conditions only, for high-speed data transmission and accurate distance measurement (to within a few centimetres).

SRS systems play a very important role in the development of applied and fundamental science, being virtually the only practical means of obtaining reliable information on the solar system, the nature and structure of the cosmos, the atmospheres and surfaces of other planets, gravitational fields and the interplanetary plasma. SRS systems are also used for such operations as guiding shuttles to the International Space Station, maintaining communications during extra-vehicular activity by cosmonauts and astronauts, and gathering samples from the surface of other planets. Apart from their immediate functions of management, collection and transmission of information, SRS activities are a powerful motor of development for related branches of science and technology, including robotics, chemistry, physics, the aerospace industry and medicine.

Radio astronomy

The term "radio astronomy" should be understood to mean the branch of astronomy based on the reception of radio waves. The objects of study are cosmic radio emissions generated by hot cosmic plasma, gases and solid bodies in space. Cosmic emissions take two forms, namely, continuous spectrum radiation and radiation consisting of spectral lines, and the methods of measurement used differ accordingly.

The largest class of cosmic emission sources comprises continuous sources, i.e. relatively evenly distributed over a wide frequency band. In order to ascertain the frequency dependence of such emissions, measurements have to be made at a number of frequencies. Since the spectrum of a continuous emission is normally smooth, there is no need for measurements at specific frequencies or frequencies that are close together. Nevertheless, the sensitivity of the observations is improved if broad frequency bands are used.

An emission in the form of spectral lines is generated by transitions of electrons from one energy level to another in atoms, ions and molecules. Spectral lines are narrow sections of the spectrum (far narrower than the wavelength) in which the emission intensity is enhanced (emission lines) or attenuated (absorption lines) by comparison with the continuous spectrum. Spectral line observations can help us to determine the chemical composition of the object under observation, its temperature, whether or not it has a magnetic field and if so its strength, and a range of other parameters including how far away it is. Observations of such emissions normally make use of narrowband receivers tuned to the frequencies of particular spectral lines.

Amplitudes of emissions measured in radio astronomy almost always exhibit a Gaussian probability distribution. With the exception of cases of narrowband spectral lines, their statistical characteristics are the same as those of the background thermal radiation from the Earth and its atmosphere or the noise produced by the receiver. Cosmic radio emissions are also very weak. In radio astronomical observations, the signal to noise ratio (S/N) is normally between –20 and –60 dB, which means that the energy input from the object being investigated is between 10^{-2} and 10^{-6} lower than the unwanted background power from the atmosphere, the Earth and the receiver circuits. Since radio astronomical signals are so weak compared to those encountered in other services, radio astronomical observations are very sensitive to radio interference. The criterion used to determine the intensity at which an interfering signal is considered to be unacceptable (harmful) is the level of unwanted emission that results in a ten per cent increase in measurement errors by comparison with errors due solely to system noise. When calculating interference, it is normally assumed that the interference level coincides with the level that results in a ten per cent increase in root mean square fluctuations at the receiver output caused by system noise, that is

$$\Delta P_H = 0.1\, \Delta P\, \Delta f,$$

where:

$\Delta P = k\Delta t$ – noise fluctuation for the spectral power density

Δt – temperature fluctuation

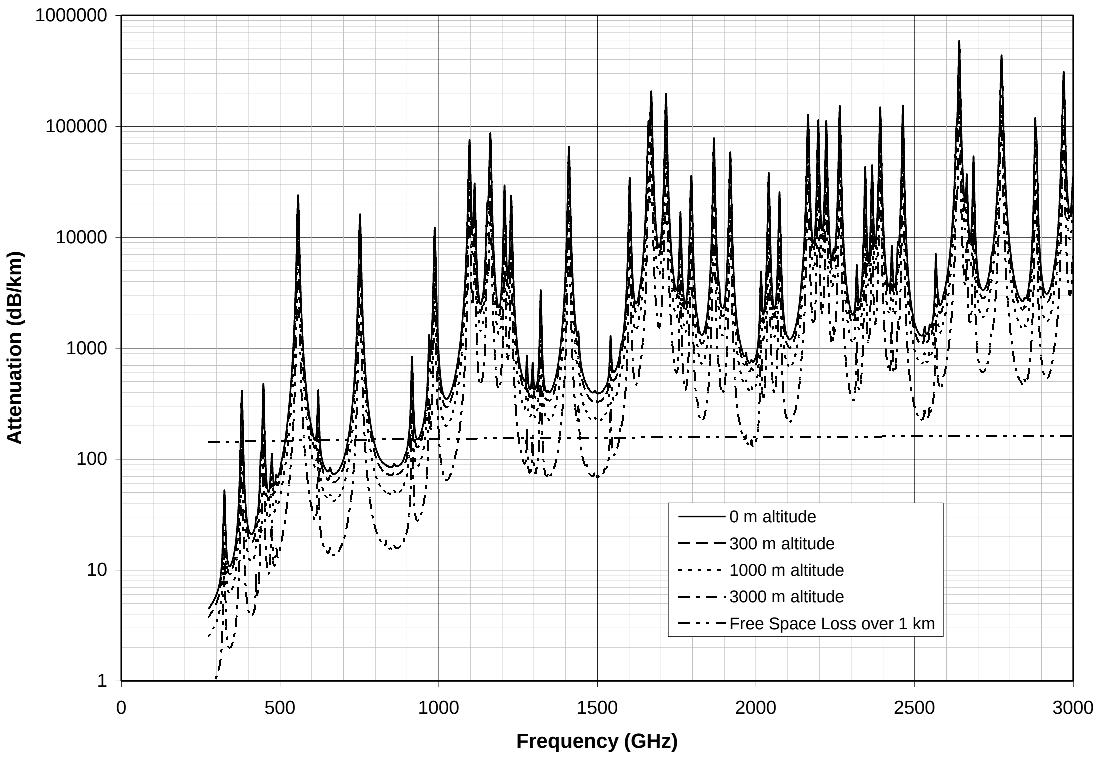
Δf – observation bandwidth.

Threshold levels of harmful interference for radio astronomy are shown in [13]. It should be noted that in a number of cases, generation of interference for radio astronomy systems results not only in a loss of measurement quality but also in actual burn out of the receiver, which is tuned to operate with very low-level signals [14].

The uses of the radio frequency spectrum for radio astronomy are many and varied and exploit all transparent frequency ranges − so-called “radio windows”. The ionosphere exerts a strong influence on observations in the frequency range below 30 GHz, and observations are normally carried out at frequencies above 50 MHz. The troposphere affects observations by absorption, mainly by oxygen and water vapour. Figure 5 shows specific attenuation in the atmosphere at four different altitudes [15]. Windows are seen in the frequency range up to 3 000 GHz and high mountains are obviously the preferred site for radio astronomy antennas.

FIGURE 5

Specific atmospheric attenuation (zenith)



Preferred frequency bands for the purposes of continuous spectrum observations are shown in Table 7. Clearly, since the received signal is very weak, the bandwidth within which measurements can be made plays an important role. It has been established that in continuous spectrum observations the minimum detectable signal is inversely proportional to the square root of the bandwidth. To ensure effective radio astronomical observation, the bandwidth must be between 2 and 10 per cent of the nominal carrier frequency.

TABLE 7

Preferred radio astronomical frequency bands for continuous emission spectra

Frequency band (MHz)	Frequency band (GHz)
13 360-13 410; 25 550-25 670; 37.5-38.25; 73-74.6; 150.05-153; 322-328.6; 406.1-410; 608-614; 1 400-1 427; 1 660-1 670; 2 655-2 700; 4 800-5 000	10.6-10.7; 15.35-15.4; 22.21-22.50; 23.6-24.0; 31.33-31.8; 42.5-43.5; 76-116; 123-158.5; 164-167; 200-231.5; 241-248; 250-275

Radio astronomy plays a key role in the study of problems in fundamental physics and cosmology. Many of the phenomena studied cannot be studied in other parts of the electromagnetic spectrum. To cite but a few examples: the emission line of neutral atomic hydrogen; cosmic microwave background radiation and its angular structure, which is of immense significance in cosmology; the huge regions of synchrotron radiation associated with radio galaxies; and regions of star formation that are hidden by dust in optical frequencies. Using radio frequencies, it is possible to achieve the highest angular resolution and the most precise measurement of angular positions and of spectral lines and their Doppler shifts. For this reason, radio astronomy, far from being a mere adjunct to traditional optical methods, plays a leading role in research carried out in many areas of astronomy and astrophysics.

Apart from this, radio astronomy, like any fundamental science, stimulates development in other branches. It is to radio astronomy that we owe the development of low-noise receivers and antennas that enable us to use a single antenna to capture signals of differing polarity. Methods developed in radio astronomy to combat radio echo are now being used successfully in WiFi-type mobile communication systems. The foundations of radionavigation theory that are used today in a range of systems were developed and confirmed in radio astronomy. The need to process huge quantities of data in radio astronomy has resulted in major improvements in automated data processing, including the development of methods for parallel data processing and new programming languages. In the medical sphere, radio astronomy has led to the introduction of X-ray diagnostics and computerized tomography. In these ways, radio astronomy generates considerable income. It is assumed that capital investment in the sector over the coming decade will amount to between USD 10 and 20 billion.

ITU-R Study Group 7

Study Group 7 comprises four working parties:

– Working Party 7A is responsible for the SFTSS and SFTSSS.

– Working Party 7B deals with data transmission systems and teleguidance in EESS, SRS and SOS.

– Working Party 7C deals with all types of sensors.

– Working Party 7D deals with radio astronomy.

Two study sessions are normally held each year, in the spring and autumn. The main results of the work of Study Group 7 are shown in Table 8. Study Group 7 is, among other things, responsible for four agenda items of WRC-12, and has drawn up some 40 reports, 100 recommendations and six handbooks. The next meeting of the working parties will take place from 26 to 30 September 2011.

TABLE 8

	WP 7A	WP 7B	WP 7C	WP 7D
Services	SFT(S)SS	EESS, Met. SS, SRS, SOS		RA
		Data transmission + TK	Sensors	
WRC-23 agenda items	Director Report on Leap second	1.13	1.12, 1.14, 9.1.a, 9.1.d	----
Research results	Series TF 16 Recommendations 1 Report Two handbooks	Series SA 59 Recommendations 34 Reports Handbook	Series RS 40 Recommendations 43 Reports Two handbooks	Series RA 14 Recommendations 12 Reports Handbook

LIST OF REFERENCES

1) Radio Regulations, Resolution 673 (WRC-07)

2) Radio Regulations, Article 1

3) Recommendation ITU-R TF.460

4) Recommendation ITU-R TF.685

5) Radio Regulations, Article 26

6) Radio Regulations, No. 5.56

7) Recommendation ITU-R P.676-8

8) Recommendations ITU-R RS.1028 and RS.1029-2

9) Radio Regulations No. 5.340

10) Recommendations ITU-R SA.1024 and SA.1019

11) Recommendations ITU-R SA.1026 and SA.1027

12) Reports ITU-R SA.2177 and SA.2183

13) Recommendation ITU-R RS.769

14) Report ITU-R RA.2188

15) Report ITU-R RS.2194.