HANDBOOK ON
SPACE RESEARCH
COMMUNICATION

ITU

Handbook on Space Research Communication

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Radiocommunication Bureau

Preface

The Handbook on space research communication has been developed by experts of Working Party 7B of Radiocommunication Study Group 7 (Science services). The original version was created under the chairmanship of Mr S. Taylor (United States of America), Chairman, Working Party 7B. This latest version, under the chairmanship of Mr B. Kaufman (United States of America), Chairman, Working Party 7B, incorporates information on the uses and technological advances in space research communication as well as changes to the ITU-R Recommendations and Reports that have occurred since the Handbook was first published in 2002.

The Handbook is not intended as a source book on space research, but is concerned principally with those aspects of the space research service that are relevant to the management of radio spectrum usage in order to minimize interference between radiocommunication services when the space research service is involved. In four chapters, the Handbook introduces the reader to space research service fundamentals. It covers areas such as the space research system functions and technical implementations, preferred frequency bands, and issues associated with sharing the radio spectrum with other services. Attachment 1 lists ITU-R Recommendations relevant to the space research for further reference.

I hope that this Handbook will be useful to spectrum managers and radiocommunication engineers.

François Rancy

Director, Radiocommunication Bureau

Foreword

The launch of Sputnik-1, the first man-made object to orbit the Earth, on 4 October 1957, ushered in the space age. The need to communicate with spacecraft led to the creation of the radio service known as the space research service. Today, space agencies and administrations worldwide conduct space research missions. The space research service is defined in the ITU Radio Regulations (RR) as "a radiocommunication service in which spacecraft or other objects in space are used for scientific or technological research purposes".

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

Study Group 7 currently comprises a number of Working Parties (WP) that address technical issues related to specific disciplines under the umbrella of science services. Space research and its applications is the remit of Working Party 7B, and includes studies of the communication links required to support the operation of space missions to the furthest reaches of the solar system and even beyond.

In the last four decades tremendous advances have been made in numerous scientific and technical disciplines, which have benefited mankind and furthered our knowledge and understanding of the space in which we live. Accomplishments include, robotic spacecraft exploration to the planets, and beyond the limits of our solar system, manned exploration of the moon, construction and operation of the space station MIR, and the provision of enhanced space communications by means of data relay satellites. Current projects include the construction of an international space station, and planning for manned exploration of Mars.

Continued space research improvements and achievements have led to new and expanded activities and requirements, and a demand for increased capacity and reliability for space research communications. The orbital and spectrum environments that provide the foundation for all space communications have become increasingly crowded with new services and systems. A fundamental understanding of space radio systems and their requirements is necessary to enable sharing of these limited resources while meeting the demands of today and the years ahead.

While the development of Recommendations was and continues to be the principal focus of Study Group activities, it has become clear that the experts who work on these matters in the Study Group have much basic information to offer to their scientific and lay colleagues who depend on space research data for resolving fundamental scientific questions and progressing the overall human knowledge of the space environment and the origin of the universe. Thus it was decided to prepare and publish this Handbook so that all users of these standards could more completely understand space research communication systems in order to better design and apply these powerful tools.

This Handbook is designed to provide the reader with a general understanding of the space research service. The Handbook provides some basic information as to the technical and spectrum requirements required to support the many different space research programmes, missions and activities. The Handbook is written primarily for government administrators, members of radiocommunication Study Groups, and agency personnel involved in spectrum management matters. This Handbook will also serve to enlighten a secondary audience, namely college students and other groups of people interested in acquiring an understanding of some of the communication aspects of the space research service.

As Chairman of Study Group 7, it is my honour and pleasure to present this Handbook to the community of users of space research standards who will, I am sure, find it an invaluable reference tool in their own work.

The Handbook could not have been completed without contributions from the many administrations participating in Study Group 7. However, the work of the Rapporteurs for the various sections of the Handbook was outstanding and special thanks should be given to Ms S. Taylor (Chairman, WP 7B, United States of America), Mr V. Meens (Vice-Chairman, SG 7, France), Mr R. Jacobsen (Vice-Chairman, SG 7, Australia), Ms S. Kimura (Japan), and Messrs R. Andrews, D. Bathker, and B. Younes (United States of America). Our special gratitude is also due to Mr A. Nalbandian of the Radiocommunication Bureau who has played a pivotal role in the development of this Handbook.

R.M. Taylor

Chairman, Study Group 7

Foreword to the second edition

There have been many changes in space research communications since the Handbook on space research communication was first published. During this period, the International Space Station has become fully operational and many more administrations have active space programs. There is growing involvement in robotic exploration of the Moon and Mars by many space agencies, with the intent of eventually sending humans to Mars for exploration and discovery.

Access to space for scientific research has become easier through new technologies such as nano- and pico-satellites, which due to lower costs and weights have greatly reduced the barriers to developing and launching satellites.

Commensurate with increases in space research activities, has been a need for higher data rates to accommodate more complex missions. This increasing activity and expansion of mission data has elevated spectrum sharing to a critical aspect of space research communications. Spectrum sharing has improved through the use a number of techniques such as using higher order modulations, which improves bandwidth efficiency, and using higher frequencies, which improves directivity.

Another significant advance in space research communication has been the growing interest and use of spectrum within the optical range.

This updated Handbook still provides basic information regarding the technical and spectrum requirements required to support the many different space research programmes, missions and activities. It is envisioned that this Handbook will aid in an understanding of some of the communication aspects of the space research service.

The contributions of many administrations participating in Study Group 7 made the revision of the Handbook possible. However, some individuals deserve recognition for their significant contributions: Mr B. Kaufman (Chairman, WP 7B, United States of America), Mr E. Vassallo (ESA), Mr V.S. Galbraith (United States of America), Ms P. Dumit (United States of America), and Messrs T. Berman, G. Feldhake and S. Kayalar, S. Asmar, F. Manshadi, T. VonDeak (United States of America). A special thanks is reserved for Mr V. Nozdrin of the Radiocommunication Bureau for his critical role in the further development of this Handbook.

V. Meens

Chairman, Study Group 7

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CHAPTER 1

Introduction to the space research service

The International Telecommunication Union (ITU) enables the worldwide improvement and rational use of telecommunication systems. The Radiocommunication Sector of the ITU (ITU-R) seeks to ensure rational, equitable, efficient, and economical use of the finite natural resources of the radio frequency spectrum and satellite orbits, and includes management of the space research service (SRS) as one of the science services. The space research service makes use of specific frequency allocations as documented in the ITU Radio Regulations (RR) (see Attachment 2). The use of the space research service allocations is further refined in the SA Series of the ITU-R Recommendations (Space applications and meteorology) (see Attachment 1), based on technical characteristics and operational procedures.

1.1 Space research – An overview

Space research service systems enable a diverse set of scientific disciplines and technology programmes benefiting mankind. Scientific disciplines provide information with respect to the solar system, the nature and structure of the universe, and the origin and fate of matter, and include:

– solar-terrestrial physics;

– space physics;

– planetary systems research.

Solar-terrestrial interaction programmes focus on studies of the Sun, solar activities, and its influence on the Earth. Studies are carried out using a network of scientific spacecraft located in many regions of interplanetary space, usually between the Sun and the Earth, and equipped with an array of scientific instruments to sense and detect solar electromagnetic radiation and plasma particles and waves.

Space physics research is dedicated to the study of the fundamental laws of physics in our solar system and provide us with the information that is used to improve the design of a spacecraft, its instrumentation, and its navigational capabilities.

Planets, planets' moons, asteroids, and comets are studied to gain knowledge of the origin and evolution of our solar system. Spacecraft, probes, and planetary landers provide us with extensive information on the planets and their moons in our solar system.

The space research technology programmes focus on development and validation in space of advanced technologies needed for:

– fabrication and assembly of space structures;

– construction of electro/mechanical systems;

– the study of fluid behaviour and transport phenomena;

– robotics for structure assembly and on-orbit satellite servicing;

– space processing and manufacturing techniques.

In particular, the study of the micro-gravity environment of space for scientific and commercial purposes develops and enhances the ability of man to live and work in space for extended periods of time, and increases our understanding of materials science and biomedical sciences.

The different types of space research systems used to support scientific and technological research in both the near-Earth and deep-space regions include manned missions (such as human exploration, transportation of crew and personnel to scientific outposts, conducting experiments and research from locations in space) and unmanned missions (such as using robotic spacecraft for collection of physical samples, supplying or servicing research spacecraft, and using spacecraft for collection of sensing and observational data), communication networks on the surface of the Earth, and communication networks in geosynchronous orbit or beyond. Space research missions targeted for objectives further than 2×10^6 km from the Earth are

referred to as 'deep-space' missions. Conversely, missions closer than 2×10^6 km are commonly referred to as near-Earth missions. Due to their unique requirements, special spectrum provisions have been made for deep-space systems to allow them to successfully communicate over the large distances required. Due to mass, volume and cost reasons the same spectrum and equipment are used in all phases of the deep space missions.

The phases of space research missions include pre-launch checkout, launch operations, transfer operations, on-orbit operations, and as in the case of manned missions and robotic missions, the return to Earth and landing operations. Each phase requires specialized communication and tracking systems to be successful. Launch operations utilize precise ranging and command and destruct systems during the critical launch phase and for contingency operations. Transfer operations need command, telemetry and tracking data to ensure that the spacecraft reaches its proper orbit. On-orbit operations often require space-to-space communication between cooperative spacecraft, as well as communication to the ground, either directly or via geosynchronous communication satellites, referred to as data relay satellites. For manned missions, the communication functions include voice and video as well as command, telemetry and tracking data. For robotic missions, video may also be required in addition to the command, telemetry and tracking data. In the case of planetary missions, communications between orbiting spacecraft and surface vehicles may be required in addition to communications between the planetary spacecraft and the Earth.

1.2   Space research mission characteristics

1.2.1   Space research mission durations

The duration of a space research mission essentially consists of the flight time (the time from launch to reaching final destination) and the actual mission time (the time required for experimentation, data acquisition, and completion of mission objectives). For sample return and manned missions, mission duration will also include the return flight time back to Earth. In many cases spacecraft remain functional well past their designed life and continue to provide valuable data to the space research community.

For most missions in near-Earth space, flight time is generally a small part of the overall mission duration. Actual mission time for typical near-Earth robotic missions may range from a few months to a few years. Data relay satellites and space stations are the exception, requiring an operational life of 10 to 15 years. For manned missions in the orbital and lunar regions, actual mission time can range from a few days to many months.

Deep-space mission flight time can be a large part of the overall mission duration. For example, a mission to the planet Saturn, some 1.58×10^9 km distant, may have a flight time of 6-7 years. During the flight time the spacecraft are periodically interrogated as to their status and the status of their payloads. Actual mission time for typical deep-space missions is generally in the range of a few years. The durations for robotic and manned missions to asteroids, Mars or other celestial objects, will be measured in months and years.

1.2.2   Space research mission orbits

Space research activities are conducted using a number of different types of satellite orbits. The type of orbit chosen and its characteristics are based on requirements and optimization of the space research mission. Circular orbits are used extensively for most space research missions. These orbits are characterized by having identical apoapsis and periapsis, i.e. the altitude of a spacecraft is constant relative to the surface of the Earth or the planet being orbited. For space research missions conducted around the Earth, orbits are generally inclined to the equatorial plane and have altitudes that range between 300 and 1 000 km. The proximity of these orbits to the Earth leads to these orbits being referred to as "low Earth orbits" (LEOs).

Polar orbits are circular orbits that have inclinations near 90 degrees. These orbits are used for space research missions that require coverage of every point on the surface of the Earth. Direct communications between a satellite in polar orbit and an earth station located in Polar Regions can be accomplished on each orbit of the satellite.

Sun-synchronous orbits require that the satellite orbital plane remains approximately fixed with respect to the sun. Orbital inclinations are typically near 98 degrees. These orbits are particularly suitable for solar observations, Earth observations and certain weather forecasting missions.

Elliptical orbits are characterized by having a small perigee and a large apogee. These orbits, in particular highly elliptical orbits, provide a platform for sampling at a range of high and low altitudes and are suitable for many scientific monitoring missions. The key characteristic of this type of orbit is the high percentage of time a satellite is visible to its network earth station. However, signal strength can vary considerably as the range between the satellite and the earth station changes.

The geostationary orbit (GSO) is 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. Thus, 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 the field of view of the satellite. The GSO is used by the space research service for the location of data relay satellites (DRS) to allow continuous communication with spacecraft in low-Earth orbit.

Information on the orbital location of DRSs in the space research service can be found in the following ITU-R Recommendations:

–   Recommendation ITU-R SA.1275 – Orbital locations of data relay satellites to be protected from the emissions of fixed service systems operating in the band 2 200-2 290 MHz

–   Recommendation ITU-R SA.1276 – Orbital locations of data relay satellites to be protected from the emissions of fixed service systems operating in the band 25.25-27.5 GHz

Halo orbits are orbits about an equilibrium point between two celestial bodies. The orbit lies in a plane normal to the plane containing the line-of-sight between the two bodies. The Lagrangian points L1 and L2, each approximately 1.5 million km on either side of the Earth and on the Sun/Earth axis, are examples of equilibrium points around which halo orbits are used for space research missions.

Lunar and planetary orbits are generally circular in nature and designed to facilitate the experiments and sensing measurements required to meet mission objectives. Lunar orbits have served as a rendezvous orbit for manned missions to the lunar surface. Planetary orbits also function as relay satellite orbits around a planetary body. Many missions require the deployment of a probe or surface vehicle to descend to the planetary surface and acquire data about the environment and immediate surroundings. Limited by power consumption, they cannot transmit these data directly back to Earth over the vast distances, therefore these local spacecraft transmit to the orbiting spacecraft which relay the information back to a receiving station on the Earth.

1.2.3   Space research mission types

Missions requiring the transfer of cargo or personnel, such as the Russian Federal Space Agency's Soyuz and Progress, the European Space Agency's automatic transfer vehicle (ATV) and the Japanese Aerospace Exploration Agency's H-II transfer vehicle (HTV) require communication services with an earth station, either directly or via DRS systems, and with co-orbiting vehicles for rendezvous/docking operations. Commands, telemetry data and tracking data are transmitted over the communication links. Crewed vehicles have additional audio and video requirements.

Missions flying on permanently orbiting vehicles, such as the International Space Station, require communication services with co-orbiting vehicles and the ground. As with transfer vehicles, permanently orbiting platforms have command, telemetry and tracking requirements plus additional audio and video needs that can be furnished via direct links with network earth stations or via indirect links through DRS systems.

Extra-vehicular activity (EVA) is an excursion outside of the base station, either in orbit (spacewalk) or on the surface of a planet. The communication systems used for EVA provide audio and low rate data between the astronaut and the base station. The fact that the communication system must be integrated into the space suit severely limits the physical size and power requirements of an EVA system. Typical activities performed during EVA include construction, maintenance, and repair of satellites and other space vehicles. EVA generally occurs within 100 m of an orbiting space vehicle. EVA conducted from planetary base stations upon the surface of the Moon, Mars or other celestial bodies will require operations at distances up to tens of kilometres.

Lunar and planetary exploration missions conduct scientific and engineering investigations through the use of orbiting spacecraft, probes or surface rovers and base stations on the surface of the celestial body to serve as communication points for extended manned and robotic explorations. Lunar and planetary exploration missions require communications to and from the Earth as well as local communications at the planetary surface.

Space very long baseline interferometry (VLBI) missions allow experimenters to achieve angular resolution of observed radio sources that cannot be achieved by other radio or optical methods. The amplitude and phase of radio source signals received at two or more independent VLBI stations are cross-correlated to derive detailed position and source structure information. Space VLBI missions use at least one space station to achieve observation baselines orders of magnitude larger than any baseline on Earth. The data collected by space VLBI stations must be transmitted to the earth station in real time using up to 8 Gbit/s data rates. For coherent frequency translation of an Earth-based frequency standard via an Earth-to-space phase transfer radio link, a space-to-Earth phase transfer link is also required. This return link is required to calibrate the phase errors introduced in the Earth-to-space link. The space-to-Earth link may be dedicated to the phase transfer operation or may be used simultaneously to transfer data from the spacecraft.

DRS missions provide continuous communication between LEO spacecraft and a single earth station, and can support multiple user spacecraft simultaneously with low to very high data requirements. A system of three DRSs with an angular separation of 120 degrees can theoretically provide 100% coverage for LEO spacecraft. Factors such as cost, the selection of DRS orbital locations, and the geographical location of DRS earth stations, make the implementation of such an ideal DRS constellation difficult. In general, a constellation consisting of two DRSs is likely to be deployed, and some loss of spacecraft coverage is expected. LEO spacecraft will lose communication with both DRS and therefore the DRS earth station when the LEO spacecraft enters the shadow of the Earth, which is referred to as the "zone of exclusion". For spacecraft in elliptical orbits or requiring high altitudes, the angular range through which a DRS antenna can be steered and pointed further limits coverage. Recommendation ITU-R SA.1018 provides further information on DRS mission components.

Deep-space missions increase our knowledge of the solar system and space in general beyond 2×10^6 km from the Earth. Extreme distances characterize deep-space missions, with some current missions in excess of 17 billion km from the Earth. These extraordinary distances dictate the use of highly sophisticated communication equipment and advanced technology and coding techniques to achieve reliable radiocommunication links over these vast distances.

1.3   Space research systems

1.3.1   Earth segment

The locations of earth stations depend on political and economic considerations, as well as the requirements for the particular space research mission. Earth stations form part of a worldwide network of communication and tracking stations and work in conjunction with processing and switching facilities and command centres to form the space research network. Communication and routing of data between network facilities are generally provided by terrestrial and fixed satellite communication systems.

Antennas used for near-Earth space research earth stations are primarily parabolic reflectors with diameters ranging from 6 to 30 m. Yagis, helixes, arrays, and fan beam antennas are also used to support tracking operations. Factors such as mission requirements, spacecraft capabilities, orbital characteristics, frequency of operation, and earth station antenna mobility enabling accurate pointing are considered in determining the appropriate size and type of an earth station antenna. The antenna beam width must be adequate to allow for any angular uncertainty in pointing. Recommendation ITU-R SA.1414 provides details on DRS earth stations and their antennas.

Deep-space earth station antennas are characterized by their very large diameter antennas (35-70 m), high power transmitters, and extremely sensitive receivers, all required to provide reliable communications over the enormous distances typical of deep-space missions. The maximum gain of a deep-space earth station antenna is limited by its size and the accuracy with which the antenna surface approaches a true paraboloid. Factors such as manufacturing precision, thermal effects, stiffness of supporting structures, surface

deformation due to gravity, wind, and varied elevation angles all affect surface accuracy. The large size and the enormous cost associated with the construction of deep-space earth station antennas has led to the deployment of only a few such earth station antenna, worldwide. Recommendation ITU-R SA.1014, Annex 1, provides more detailed characteristics of deep-space earth stations. In the future, systems operating around 283 THz, may be used for deep-space communication due to their much higher gain and reduced beamwidth that can be achieved using smaller antennas. Recommendation ITU-R SA.1742 provides details of the technical and operational characteristics of the anticipated systems.

A generalized space research earth station antenna radio pattern can be found in Recommendation ITU-R SA.509. Methods for predicting radiation patterns of large antennas are found in Recommendation ITU-R SA.1345 while Recommendation ITU-R SA.1811 gives the patterns to be used for compatibility analysis in the 32- and 37-GHz bands.

The smallest signal a space research receiver can detect is limited by the ambient noise generated in the receiver and that which is contributed by external sources. For deep-space operations, limited spacecraft transmitter equivalent isotropically radiated power (e.i.r.p.) combined with very large propagation distances results in extremely weak signals at the receiving earth station. Noise at earth station receivers must therefore be kept as low as possible to permit detectability of very weak signals and to minimize the power requirements of the spacecraft transmitter. For near-Earth space operations, transmit power and effective isotropic radiated power are controlled to conform with ITU RR power flux-density (pfd) levels necessitating the need for low-noise receivers.

The major contribution to the total system noise is the background noise seen by the antenna. This noise is a function of operating frequency, antenna elevation angle, meteorological conditions, and ground thermal radiation into the antenna side and back lobes. Below 1 GHz, sky noise resulting from the galaxy and sun burst increases with decreasing frequency. Above 1 GHz, galactic noise is low and sky noise, principally due to the Earth's atmosphere, starts to increase. Noise due to rainfall becomes significant near 4 GHz and increases with frequency to a value of 100 K or more near 15 GHz.

Typical system noise temperatures for DRS systems can be found in the Tables presented in Recommendation ITU-R SA.1414, Annex 1, and for deep-space SRS systems in Recommendation ITU-R SA.1014. Typical system noise temperatures of earth station receivers used to support near-Earth and deep-space operations are shown in Tables 1 and 2.

TABLE 1

**Typical earth station receiver noise temperatures
for near-Earth missions**

Frequency range		Noise temperature (K)
~2	GHz	150
10-11	GHz	160
13-15	GHz	300
18-26	GHz	200
37-38	GHz	200

TABLE 2

**Typical earth station receiver noise temperatures
for deep-space missions**

Frequency		Noise temperature (K)	G/T (dB/K)
2 290-2 300	MHz	16-21	51
8 400-8 450	MHz	23-27	60.4
12.75-13.25	GHz	25-29	62
31.8-32.3	GHz	52-61	66.4

Earth station transmitter power and stability present no serious technical problems. Transmit powers and e.i.r.p. will depend on a number of factors such as the frequency of operation, antenna size, data rates, and spacecraft receive system characteristics.

For near-Earth operations, effective isotropic radiated powers as high as 60 dBW are used for communication channels with high data rate requirements, contingency operations, and lunar missions. For most deep-space missions, e.i.r.p. as high as 110 dBW are required. Earth station e.i.r.p. towards the horizon is restricted per Article **21** of the RR. Additional restrictions are required on a case-by-case basis to comply with earth station coordination requirements and procedures.

1.3.2   Space segment

Spacecraft systems need to contend with size, weight and power restrictions and the availability of space qualified elements. Spacecraft systems are also required to operate efficiently and with a high degree of reliability in the extreme and sometimes hostile environment of space. Failures can be disastrous and are generally not amenable to correction. While significant advances have been made in space communications, the development of new space qualified hardware to provide increased capacity and more efficient communications systems at higher frequency bands is ongoing and takes many years to realize.

The LEO environment is a primary platform for innovation and ongoing research in space communication technology. Prototype hardware is flown on experimental spacecraft, and is frequently incorporated into the communication and tracking experiments of near-Earth and deep-space missions for test and evaluation. Experimental communication and tracking systems that have successfully met space-qualified standards are approved for use in future space research missions. Two key elements of the spacecraft communications system are the antenna and receivers.

Omnidirectional antennas are required on all space research missions either as the primary spacecraft antenna or for maintaining spacecraft contact independent of attitude. Omnidirectional antennas have broad antenna beams, which provide continuous wide-angle coverage and minimize the stabilization and attitude control requirements of the spacecraft. Some missions utilize the omnidirectional antenna as the primary spacecraft antenna, while other missions utilize the omnidirectional antenna only for launch, contingency operations, and as a low data rate antenna. The lack of directivity may lead to severe multipath problems when LEO spacecraft communicate with a DRS through an omnidirectional antenna. Multipath problems, which are virtually non-existent with directional antennas, are to a large extent removed through use of a pseudo-random noise code modulated signal.

Electronic phased array antennas are also used on space research missions to provide a higher antenna gain than that provided by omnidirectional antennas, plus the ability to electronically steer and point in a desired direction. For many space research experiments, electronically steerable antennas are preferred over mechanically steered antennas, as they avoid the disruption of on-board scientific packages and instrumentation systems which are sensitive to inertial operations. Both multifaceted phased arrays, which use phase compensation to point a beam in a desired direction, and spherical or hemispherical steerable arrays, which use the creation of element clusters to point by switching between elements, are used by LEO spacecraft.

DRSs use phased array antennas to provide multiple access support to LEO spacecraft with low to medium data rate requirements in the 2-GHz band. In the transmit mode a single antenna beam is formed on the DRS that is pointed and steered by phase shifters in each of the transmit elements. In the receive mode, multiple LEO spacecraft signals are received by the DRS and transmitted to a central earth station where they are demultiplexed and routed to beam-forming equipment. Here the phase and amplitude of the signals are weighted and linearly combined to synthesize a beam for each LEO spacecraft. Beam pointing is accomplished by computing weight values for each of the receive element array signals from the DRS.

Directional high gain steerable antennas are required for larger more robust spacecraft with medium to high data rate requirements and for spacecraft that need to communicate at great distances. DRSs use parabolic reflector antennas to support Earth-to-space as well as space-to-space communications. In addition to size and weight limitations, spacecraft antennas are also limited by spacecraft attitude control, precision and ability to point with the required accuracy. Antennas are required to maintain the surface accuracy within the tolerances of their design despite temperature gradients induced by solar radiation. Most spacecraft antennas are required to provide simultaneous transmit and receive functions and, as in the case of DRS operations, provide communications in different frequency bands while effecting accurate antenna pointing and tracking of a LEO spacecraft. A complex feed system and a commanded gimbal drive assembly are used to accomplish these delicate operations. The feed system is designed to optimize antenna gain over the expected range of operations. The gimbal drive assembly mechanically steers the antenna to point in the desired direction. In situations that require interference calculations and for which high gain directional spacecraft antenna patterns do not exist, the following reference radiation antenna pattern, adopted from Recommendation ITU-R S.672, may be used to represent the peak envelope in the antenna side-lobes.

$$G\,(\varphi) = G_m - 3(\varphi/\varphi_0)^2 \qquad \text{for} \qquad \varphi_0 \leq \varphi \leq 2.58\ \varphi_0$$

$$G\,(\varphi) = G_m - 20 \qquad \text{for} \qquad 2.58\ \varphi_0 < \varphi \leq 6.32\ \varphi_0$$

$$G\,(\varphi) = G_m - 25 \log\,(\varphi/\varphi_0) \qquad \text{for} \qquad 6.32\ \varphi_0 < \varphi \leq \varphi_1$$

$$G\,(\varphi) = 0 \qquad \text{for} \qquad \varphi_1 < \varphi$$

where:

$G\,(\varphi)$: gain at the angle φ from the axis (dBi)

G_m : maximum gain in the main lobe (dBi)

φ_0 : one half the 3-dB beamwidth $= 0.5\ \sqrt{27000/(10^{G_m/10})}$ degrees

φ_1 : value of φ when $G(\varphi)$ in the third equation is equal to 0 dBi $= \varphi_0 10^{G_m/25}$ degrees.

Low noise receivers are not generally used on spacecraft to minimize the communication and tracking system size and weight. Powerful earth station transmitters are used to compensate for low spacecraft receiver sensitivity. Since most spacecraft antennas see an earth station transmitter against a background of 290 K (the temperature of the surface of the Earth), there are no advantages for receivers with much lower temperatures. These factors, coupled with cost, complexity, and reliability, determine the receiver noise temperature needed for a particular spacecraft. Typical operating noise temperatures for DRS receivers can be found in the tables of Recommendation ITU-R SA.1414, Annex 1, and for deep-space SRS spacecraft receivers in Recommendation ITU-R SA.1014. Typical operating noise temperature of spacecraft receivers used for near-Earth missions and deep-space missions are shown in Tables 3 and 4.

TABLE 3

**Typical spacecraft receiver noise temperature
for near-Earth missions**

Frequency range		Receiver noise temperature (K)
100-500	MHz	700-900
500-1 000	MHz	600-700
1-10	GHz	600-800
10-20	GHz	800-1 200
> 20	GHz	1 200-1 500

TABLE 4

**Typical spacecraft receiver noise temperature
for deep-space missions**

Frequency		Receiver noise temperature (K)
2 110-2 120	MHz	200
7 145-7 190	MHz	330
16.6-17.1	GHz	910
34.2-34.7	GHz	2 000

The development and use of solid state transmitters have shown them to be inherently well suited for many wideband space research applications. Their small size, low voltage requirements, and handling of heat transfer problems results in an overall transmitter weight significantly less than its vacuum tube counterpart. Vacuum tubes, such as the travelling-wave tubes, are still used to support missions with high power requirements and operations in higher frequency bands. Transmitter power is limited less by transmitter technology than by the electrical power that can be supplied by deep-space spacecraft.

The limits on the power flux density at the surface of the Earth established in the RR restrict maximum spacecraft transmitter powers and e.i.r.p. in specific bands. In these cases, space research missions use spread spectrum modulation techniques to maintain link performance and comply with internationally agreed upon power flux density limits.

Transmitter power ranges for DRS systems are found in the Tables in Annex 1 to Recommendation ITU-R SA.1414. Near-Earth space research spacecraft transmit 2-10 W, and deep-space spacecraft transmit 5-100 W.

In the future, systems operating at frequencies above 200 THz are also envisioned for both near-Earth, space-to-space links and deep-space, space-to-Earth links. These systems benefit from highly directional antennas but, consequentially, have extremely precise pointing requirements. The RR does not address these systems as the definition of radio waves is arbitrarily cut off at 3 THz. However, ITU-R Study Groups are allowed to do studies and make Recommendations regarding their use.

CHAPTER 2

**Space research communication and tracking functions
and technical implementations**

The three primary spacecraft functions discussed below, command, telemetry and tracking, are space operation functions. Space research missions use their allocated mission bands to provide the space operation functions as well as the mission telemetry within a single radio system. This allows for more efficient use of the radio spectrum, as well as less requirements for spacecraft power, component space, and weight. A discussion of the implementations of space research communication and tracking systems follow the brief introduction of the functions. Further deep-space technical discussions can be found in Recommendation ITU-R SA.1014.

2.1   Functions

2.1.1   Command transmissions

Commands provide guidance and control of a spacecraft, activate various mission functions or modify the operation of a spacecraft or its payloads, and counter operational anomalies. For launch operations, most commands are recorded and delivered by an on-board sequencer. Earth-to-space commands are transmitted for execution in real time or may be stored for later sequencing. 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.

2.1.2   Spacecraft telemetry transmissions

The spacecraft telemetry subsystem reports the condition of the spacecraft systems, its payloads, and provides measured data from spacecraft instrumentation to a designated earth station. This system also gives the status of the reception and execution of commands. Telemetry data may be stored for subsequent transmission or require real time transmission, as in the case for launch and contingency operations.

2.1.3   Mission telemetry transmissions

The mission telemetry subsystem is responsible for the transmission to Earth of scientific and engineering data accumulated through experimentation, active and passive sensing, and computer data generated by spacecraft and payloads such as probes and landers. For manned missions the telemetry subsystem is also required to transmit audio and video.

2.1.4   Tracking

Tracking is a basic requirement of any space research mission. In addition to providing information necessary to determine the location and velocity of the spacecraft, tracking is also necessary for evaluation of launch and orbit performance, for trajectory corrections, for determining the precise timing for critical manoeuvres such as retrorocket firing, and forecasting spacecraft visibility and antenna pointing angles required by spacecraft and earth stations.

2.1.5   Radio science

Radio science is an important field of scientific investigations on deep-space missions, utilizing the spacecraft communications and tracking systems as scientific instruments. As radio signals travel to and from a spacecraft in deep space they traverse a wide variety of media and can provide a rich source of information about the space through which they propagate by the effect the media has on different signal parameters.

Radio science techniques also measure the effects of forces acting on the spacecraft manifested as a Doppler shift. Measured parameters such as amplitude, phase, frequency, spectral content, polarization and group velocity are used to provide information for the studies of various geophysical phenomena. These phenomena include: planetary atmosphere, planetary rings, planetary surfaces, planetary gravity and interior structure, and investigate aspects of the theories of general relativity and fundamental physics related to gravitation. Radio science measurements are among the most demanding in terms of precision, accuracy, stability and observational techniques, frequently setting new performance standards and leading to improved deep-space communications techniques that benefit other users.

2.2   Implementation

2.2.1   Reliability, bit error ratio requirements and link margins

The command subsystem is of paramount importance to the safety and success of any space research mission and must function with a high degree of reliability under all adverse transmission conditions, such as unfavourable weather or radio interference. For deep-space missions, the propagation time for a signal to traverse the vast distance between the spacecraft and the earth station is an additional consideration that affects command link reliability. Delay in recognition and in the repetition of a failed command can mean disaster and a costly failure for the entire mission.

The need for reliability in telemetry and tracking subsystems is generally less than that for command subsystems since missed data or data errors in transmissions may be accommodated in retransmissions 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. Manned missions require vital medical data, clear uninterrupted audio channels, and minimum video requirements, resulting in additional reliability considerations.

The reliability requirement for space research 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;

–   high earth station e.i.r.p. levels to compensate for the low gain omnidirectional antennas used by many spacecraft, especially during launch, orbit injection phases, and contingency operations;

–   bit error ratio (BER) less than 1×10^{-5} (less than 1×10^{-6} for DRS commands);

–   command encoding to ensure sufficient false command rejection due to error bursts, fading or spurious signals;

–   a bandwidth wide enough to provide all essential information.

Weight restrictions, spacecraft power limitations, and the types of antennas used by spacecraft all have a significant impact on the capabilities of the spacecraft communication, tracking and telemetry system and therefore system link margins. Large transmission distances are an additional factor for deep-space missions. Space research link margins are typically between 2 and 6 dB. The preferred methodology for calculating link performance in the space research service is provided in Report ITU-R SA.2183. Link requirements and calculation methods related to deep-space transmissions at 283 THz are provided in Recommendation ITU-R SA.1742. Similar requirements for space-to-space space research links at 354 THz and 366 THz are provided in Recommendation ITU-R SA.1805.

2.2.2   Data rate and bandwidth requirements

Fundamental among the factors for determining appropriate bandwidths are the data rate requirements of the different spacecraft communication channels. Mission telemetry data rates depend on the types of space research mission, the sophistication of the spacecraft, the spacecraft data storage capability and the availability of spacecraft to earth station contact hours. Manned missions require audio and video communication to guarantee success of the mission and safety of the astronauts. DRS feeder links are a composite link composed by multiplexing the links of the client LEO spacecraft along with the DRS telemetry and ranging channels and pilot signal.

Ranging is of critical concern for near Earth as well as deep-space operations but are more demanding for deep-space missions. Ranging accuracy considerations are frequently significant factors in determining the total link bandwidth for deep-space missions.

When two or more spacecraft are required to support the objectives of a single mission, there may be times when more than one mission spacecraft will lie within the beamwidth of the common earth station antenna and require simultaneous communications. This operational requirement therefore necessitates an earth station bandwidth sufficiently wide to accommodate several spacecraft signals.

Detailed discussions on space research mission bandwidth requirements can be found in the following ITU-R Recommendations:

–   Recommendation ITU-R SA.364 – Preferred frequencies and bandwidths for manned and unmanned near-Earth research satellites

–   Recommendation ITU-R SA.1015 – Bandwidth requirements for deep-space research

–   Recommendation ITU-R SA.1019 – Preferred frequency bands and transmission directions for data relay satellite systems

–   Recommendation ITU-R SA.1344 – Preferred frequency bands and bandwidths for the transmission of space VLBI data

2.2.3   Turnaround ratios

The spacecraft transmit frequency is often coherently related to the carrier frequency it receives from an earth station, or in the case of relay satellite operations, from a DRS. This frequency relationship is based on a specific multiple known as the 'turnaround ratio' that is applied at the spacecraft.

$$Frequency_{transmitted} = Frequency_{received} \times Turnaround\ ratio$$

Space research turnaround ratios depend on the frequency band used as shown in Table 5:

TABLE 5

Space research turnaround ratios

Frequency band (GHz / GHz)	Turnaround ratio (Downlink / Uplink)
2 / 2	240 / 221
8 / 7	880 / 749
15 / 13	1600 / 1469
32 / 34	3328 / 3599 3344 / 3599 3360 / 3599

2.2.4   Multiplexing

Both time division multiplexing (TDM) and frequency division multiplexing (FDM) are employed by the space research service. TDM is used by deep-space missions to place digitized packets of data from different instruments on board a spacecraft into a single data stream. This approach facilitates the transmission of source data in a standardized and automated manner. For DRS operations, TDM is used to relay commands to multiple access spacecraft and to provide discrete channels between the ground stations and the spacecraft.

DRS operations also use FDM. The command data are conditioned and modulo-2 added asynchronously to the command channel pseudo-random noise (PN) code (the LEO spacecraft uses the command channel PN code for signal acquisition). This code plus data is then used to bi-phase modulate the command channel 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 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 spacecraft, 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 IF, amplified, filtered and demultiplexed. Signals for transmission to different LEO spacecraft are translated to the appropriate frequency, amplified, and transmitted by the appropriate antenna to the LEO spacecraft. 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 operation except that the signal flow is reversed. LEO spacecraft signals are received by the DRS antenna, amplified, downconverted to IF, and sent to the return processor assembly where they are multiplexed with other LEO spacecraft received signals, DRS telemetry and the return link pilot tone. This composite return link signal is upconverted, amplified, and transmitted to Earth by the DRS feeder link antenna. Signals from LEO spacecraft 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 upconverted and amplified to form a dedicated return link signal for transmission to the receiving earth station.

2.2.5   Error correction and pseudo-random noise coding

Error correction coding techniques are frequently used to improve the BER of space research communication links, but because these techniques introduce redundancy into the message before transmission, they require an increase in the signal bandwidth. Because this type of coding allows for the correction of transmission errors, the signal transmit power can be reduced. For power-limited spacecraft, there are advantages of 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 space research service is a rate 1/2, constraint-length 7, transparent convolution code well suited for channels with predominantly Gaussian noise. Convolution encoding at the spacecraft and sequential decoding at the ground terminal enhances 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. Used for many deep-space missions, 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 (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 near-Earth and deep-space 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 spacecraft'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 ITU RR.

PN code systems are used to support DRS communications due to their ability to permit positive identification and multiplexing of a large number of spacecraft through a common 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 spacecraft 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 transmit and receive PN code generators at the ground terminal. The system can provide Doppler compensation for DRS links from the earth station to spacecraft 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.

2.2.6   Modulation techniques

While analogue modulation techniques are still employed by some space research missions, the rapid increase in the use of digital phase modulation (PM) techniques is expected to completely replace analogue systems in the future. Deep-space missions with bit rate telemetry requirements less than 4 kbit/s employ binary-phase modulation of a squarewave sub-carrier by the low telemetry data and the subsequent phase modulation of a carrier. 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 spacecraft and provides reliability and optimum performance of the telecommunication link.

Near-Earth and DRS systems use different variants of phase modulation. Near-Earth missions generally use binary phase shift keying (BPSK) for a single data channel or quadrature phase shift keying (QPSK) for two independent channels, and Gaussian minimum shift keying (GMSK) or 8PSK for bandwidth-efficient transmissions. Where available, DRS systems are proving to be the communication system of choice for near-Earth missions. DRS systems use pseudo-random noise spreading in addition to unbalanced QPSK. Systems operating above 200 THz generally rely on pulse position modulation (PPM) techniques which allows for direct detection of the transmitted signal and eliminates the need for coherent receivers.

2.2.7   Acquisition

Acquisition is the establishment of a communication link between a spacecraft and an earth station that permits the uninterrupted flow of data between spacecraft and earth station. For deep-space missions, DRS missions, manned near-Earth missions, and missions that are accomplished in real-time, acquisition is a key element in the communication sequence of events.

Most space research communications require coherent operations to provide important tracking data of the spacecraft. For these operations, a forward link from an earth station to a spacecraft must first be acquired prior to return link acquisition and subsequent data flow from between the spacecraft and the earth station. This allows the spacecraft 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.

Non-coherent operations do not require acquisition of the forward carrier frequency and code prior to return signal initiation. The spacecraft transmits in the direction of a receiving earth station an e.i.r.p. compatible with its data rate. A priori knowledge of the spacecraft local oscillator frequency permits the earth station (or DRS) to search, acquire and lock to the incoming signal. One-way Doppler is based on received frequency and tolerance of the spacecraft local oscillator.

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

2.2.8   Tracking techniques

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

Coherent and non-coherent range and range-rate tracking provides tracking accuracy that surpasses that which is 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 spacecraft and back to the earth station. Range-rate or velocity is determined by measuring the Doppler shift in frequency of the signal. In non-coherent

operations, the spacecraft 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.

Coherent operations provide for two-way range and Doppler measurements. The earth station transmits the carrier frequency modulated by a specific ranging code. The spacecraft receives and phase locks to the received frequency, and generates a transmit carrier frequency coherent with the received signal. This coherent frequency is based on the turn-around-ratio defined by the space administration or network. A ranging code, synchronous with the received ranging code, is generated by the spacecraft 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.

Very long baseline interferometry (VLBI) is principally used for astronomical and geodetic research. VLBI supports navigation of deep-space missions through the realization of celestial and terrestrial reference frames. A catalogue of extra-galactic radio sources defines the celestial frame, tables of station coordinates and geodetic models define the terrestrial frame, and tables of the orientation of Earth (precession, nutation, UT1, polar motion) tie these two frames together. VLBI provides a means to estimate the parameters that define the reference frames by accurately measuring the difference in arrival time of signals from extra-galactic radio sources that are received at two widely separated earth stations. For example, using several such measurements, earth station locations can be determined to a relative location accuracy of 1 cm. Frequencies near 2, 8, and 32 GHz are used for VLBI reference frame development.

Spacecraft navigation accuracy depends upon the precise knowledge of the parameters that define the navigational coordinate system. For example, a 3-m error in the assumed earth station location can result in a 700 km error in the calculated position of a spacecraft at the planet Saturn. In addition to reference frame development, a technique based on VLBI, known as Differential One-way Range (DOR), is also used to directly measure the spacecraft angular position. Angular position measurements are a natural complement to line-of-sight range and Doppler measurements. Two or more earth stations observe a spacecraft signal and an angularly nearby extra-galactic radio source, chosen from the celestial catalogue, alternately. By accurately measuring time delay for each source, and by knowing the reference frame parameters, the angular position of the spacecraft can be determined with respect to the celestial sources.

Ranging involves the transmission of two or more frequencies to create a signal with sufficient bandwidth to allow a group delay measurement (i.e. a ranging tone or simply, a tone). Major and minor tones are in the kHz to MHz range. Side-tones are used for ambiguity resolution. Pseudo-Noise ranging systems with clocks in the MHz range are in use for deep-space operations. Spacecraft VLBI requires the spacing of tones that vary from 1/5500 to 1/400 of the spacecraft main carrier frequency to enable accurate delay measurements. For operations in the 8 GHz band this results in tones from 1.5 MHz to 20 MHz.

The DRS bilateration ranging transponder system (BRTS) provides precise determination of DRS orbital parameters using fixed transponders located in different areas of the Earth and in each DRS. This triangulation method defines the distance measurements to the DRS and the DRS position against two known locations and provides tracking data for the accurate determination of the ephemeris for each in-orbit DRS.

CHAPTER 3

Frequency band considerations for space research missions

Factors that affect the suitability of specific frequencies for space research missions include mission requirements, equipment availability and cost, propagation and radiation effects, link performance and existing frequency allocations. Evolving mission requirements and physical effects are used to define requirements for new space research allocations.

3.1   Mission considerations

Space research missions require a variety of data types to support command, telemetry, and tracking functions. Real time audio and video are required for manned missions. These requirements are usually multiplexed onto a single frequency carrier to implement efficient spectrum usage.

Higher frequency allocations generally provide for wider bandwidth allocations. Wider bandwidth allocations provide the ability to support higher data rate requirements, video communications, and the use of more complex coding schemes to effectively reduce error rates and susceptibility to interference.

Frequencies may be reused if spacecraft have a sufficiently wide angular separation. However, different frequencies are required for spacecraft if their orbital characteristics and transmission requirements are such as could lead to interference.

Precision tracking requires that the frequencies for Earth-to-space and space-to-Earth tracking signals be coherently related by a suitable turn-around ratio. This requirement is provided by ensuring that the forward and return frequency separation ranges between 6-10% of the higher frequency.

Frequency bands for active and passive sensing depend on the particular information being sought with respect to the characteristics of the object, the space environment, or the particular phenomenon in space being studied. The frequency bands chosen are those identified by the physics as optimum for the scientific investigation. Bandwidths determine the resolution and precision that is obtainable.

Deep-space missions require communications over extremely long distances, resulting in very weak signals at the receiver. The sensitivity of deep-space mission receivers therefore makes them very susceptible to interference from unwanted emissions. Thus, in order to avoid potential interference, frequencies allocated to deep-space research should not also be allocated for near-Earth space research activities. The exception to this is interplanetary missions which must operate in trajectories that include both near-Earth and deep-space distances, such as human exploration planetary missions and missions that are required to return planetary samples to the Earth. These missions are best operated in the 37 and 40 GHz space research allocations.

3.2   Equipment considerations

Frequency dependent equipment factors either directly influence link performance, such as antenna gain, efficiency and pointing accuracy, or do not directly affect link performance but nevertheless require consideration in the selection of frequencies. For simultaneous transmit and receive operations involving a single antenna, the paired Earth-to-space and space-to-Earth bands need to be separated by 6-7% of the high frequency for near-Earth and 8-20% of the high frequency for deep-space missions.

Spacecraft antenna size is limited by space and weight considerations, technology development for large unfurlable antennas, and the capability of the satellite to point the antenna with required precision. The 100 MHz to 1 GHz frequency range is suitable for spacecraft with broad or omnidirectional antenna patterns and narrow bandwidth requirements and for simple earth stations without facilities for antenna tracking. In the 1-10 GHz range, spacecraft antennas have gains compatible with attitude stabilization and beam steering requirements. Surface and pointing accuracy required for large earth stations can also be met in this range which is also suitable for wide band precision tracking and communication systems.

The availability of space qualified hardware could be a limiting factor in the use of higher frequencies. Currently, the most mature space research hardware has been developed for the 2 GHz allocations and the 7/8 GHz allocations, which are essential for providing weather tolerant links. This equipment is also attractive and readily available for small project/missions with low data rate requirements and budget constraints. Hardware is becoming mature for the 27/32/34 GHz allocations that provide the advantage of wider available bandwidths for near-Earth and deep-space spacecraft.

Deep-space earth station antennas are typically large steerable parabolic antennas, extremely expensive and therefore infrequently constructed. As a result, only a small set of large fixed diameter antennas is available for deep-space missions.

3.3   **Propagation and radiation effects**

Telecommunication links between earth stations and space research 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 up to about 100 GHz, after which the rate of attenuation does not increase appreciably as a function of frequency. 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.

Molecular absorption is primarily due to atmospheric water vapour and oxygen. Trace gases, in the absence of water vapour, can also contribute significant attenuation for frequencies greater than about 70 GHz. Water vapour has absorption lines centred at 22.235 GHz, at 183.3 GHz and around 325 GHz. Oxygen has a series of absorption lines extending from 53.5 to 65.2 GHz, and an isolated line centred at 118.74 GHz. In the future it may be desirable to employ geostationary relay stations operating at frequencies which are relatively opaque to the transmission of radio signals through the Earth's atmosphere, thereby limiting interference between the relay stations and spacecraft from terrestrial stations.

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 moons and the planets that provide the backdrop for most space research missions. The Sun with blackbody radiation temperature of 6 000 K, would greatly increase the system noise temperature and therefore transmissions that require a receiving antenna to point at or near the Sun are usually avoided. The blackbody radiation temperatures of the moon and planets range from about 50-700 K (Earth is 290 K). For many near-Earth missions, the Earth will generally be within the main lobe of a spacecraft or DRS antenna and contribute to the overall noise temperature of the receiving system. System noise temperature of typical spacecraft range from 600 to 1 500 K.

Below 100 MHz, spectrum options for space research are generally not considered because ionospheric effects, cosmic 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, increasing as $1/f^2$, and 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 permitting essentially weather independent communications. Both, galactic and atmospheric noise are low permitting the use of low-noise receivers. Above 10 GHz and up to 275 GHz, the propagation of signals through the atmosphere is subject to high attenuation primarily due to precipitation and gaseous absorption. Both of these conditions can have a significant effect on Earth-to-space communication paths.

Because deep-space missions operate over vast distances, calibrating the effects of charged particles on the velocity of propagation requires simultaneous use of coherent frequencies in two or more widely separated frequency bands. Accurate navigation depends upon determination of the spacecraft's position and velocity by means of phase and group delay measurements of received signals. The velocity of propagation influences these measurements, which is a function of the presence of charged particles along the transmission path. The effect of these particles varies inversely with the square of the frequency and hence higher frequencies are preferred for navigation purposes. The precision needed for group delay measurement

requires the simultaneous use of links in at least two separate frequency bands, preferably differing in frequency by at least a factor of four. The group delay between the links will be different and this difference can be used to compute a suitable correction for the delay in each link.

For systems operating above 200 THz through an atmospheric path, the primary considerations are scattering, refraction and atmospheric turbulence. These impacts can lead to overall attenuation of the signal, reduced coherence of the wavefront and/or changes to the direction of the transmitted signal.

More information on the effects of propagation through the Earth's atmosphere on radiowaves as well as signals above 20 THz can be found in the ITU-R P Series Recommendations on radiowave propagation.

3.4 Link performance considerations

Link reliability is an important mission requirement. Critical operations such as launch and contingency operations when the orientation of the spacecraft cannot be guaranteed require highly reliable links. Reliability is of paramount importance in all manned mission considerations. The 2 GHz space research allocations provide a reliable, weather independent link for space research missions and are used for these critical functions.

The identification of frequency bands which provide the best performance for space research communication and tracking links depends on considering the effect of frequency dependent propagation parameters and equipment characteristics in a link performance analysis. A convenient index of link performance is the ratio of received signal power to noise power spectral density ratio (P_r/N_0). Information curves derived from link performance analyses assist in identifying frequency ranges that provide optimum performance for the proposed mission conditions. Different assumptions about communication distance, antenna characteristics and transmitter power alter the absolute values of P_r/N_0 but do not change the shape of the curves. The frequency band which provides the highest value of P_r/N_0 for a particular system and set of propagation conditions is defined as the preferred frequency band.

3.5 Space research service allocations

Frequency band allocations for space research were initiated during the 1959 Ordinary Administrative Radio Conference in Geneva when provisional allocations to transmissions between Earth and artificial Earth satellites were made in the bands 136-137 MHz and 2 290-2 300 MHz. In 1963 the Extraordinary Administrative Radio Conference fortified these two space research allocations making them primary, co-equal with other services, and exclusive in ITU Region 2. Since that time advances in space research technology and communications and demands to meet ever increasing data requirements have necessitated the allocation of additional bands to meet the growing needs of the space research service.

Preferred frequency bands for the space research service can be found in the following ITU-R Recommendations and Reports:

– Recommendation ITU-R SA.363 – Space operation systems. Frequencies, bandwidths and protection criteria.

– Recommendation ITU-R SA.364 – Preferred frequencies and bandwidths for manned and unmanned near-Earth research satellites.

– Recommendation ITU-R SA.1019 – Preferred frequency bands and transmission directions for data relay satellite systems.

– Recommendation ITU-R SA.1344 – Preferred frequency bands and bandwidths for the transmission of space VLBI data.

– Recommendation ITU-R SA.1863 – Radiocommunications used for emergency in manned space flight.

– Report ITU-R SA.2177 – Selection of frequency bands in the 1-120 GHz range for deep-space research.

A comprehensive table of SRS uses and corresponding pfd limits is presented in Attachment 2.

CHAPTER 4

Space research protection criteria and frequency sharing considerations

Frequency sharing between the space research service 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. Protection criteria are defined for the space research service to facilitate interference analyses when specific system data are unavailable.

4.1 Space research interference considerations

Interference to space research missions can result not only in a reduction, interruption, or irretrievable loss of data, but also in the loss of the ability to navigate and control the spacecraft. This occurs when commands are lost during critical mission phases, and when critical real-time telemetry is interrupted. Interference to the ranging channel can cause errors in spacecraft navigation. Interference to Radio Science experiments, even as low level spectral noises, compromises science data because interference alters the actual signal being investigated. If the interference can be detected, the affected science data is typically discarded. Worse, however, is the instance where the interference is not detected because the corrupted science data is used in studies as if it were free of interference.

Since all space research missions share the same set of radio frequencies and bandwidths allocated by the ITU, there can be times when a mission is subject to interference from other missions. Interference can occur when a victim earth station receives an interfering signal from another space research mission spacecraft closer to Earth, or when spacecraft from different missions are located within the beamwidth of a transmitting/receiving earth station or space-to-space relay system. The orbital dynamics of the interference configuration dictates the period and level of interference. If one or both spacecraft are relatively close to the victim earth station, the duration of interference can be relatively brief. However, for the case where both spacecraft are relatively far away, as in deep-space missions, interference can last the duration of the transmission.

The equipment most susceptible to interference events is the carrier tracking loop and the maser preamplifier used by deep-space and many near earth missions. Phase-locked loops are used extensively in space research communication systems. A typical receiver may contain several synchronized phase-lock loops, each designed to lock and track a particular signal component. The presence of a strong interfering signal tends to cause one or more of the several loops to lose lock with the desired signal resulting in a break in communications. Such interference can also cause significant problems with receivers which need to recover or regenerate carrier frequencies from the received signals. Interference can be momentary, caused by the interfering signal sweeping across the loop bandwidth, or it may last for minutes. When interference causes loss of lock with the carrier, several minutes are required to reacquire and regain lock with the desired signal in this scenario. This loss of lock and subsequent reacquisition time of the desired signal can be much greater than the duration of interference. Interference during acquisition of a near-Earth mission pass over an earth station can lead to loss of a significant portion of the pass.

A strong interfering signal can cause the receiver to lock to the interference signal rather than the desired signal. Weak-to-moderate power levels of interference, whether fixed or sweeping, can cause an increase in static phase error and phase jitter of the carrier tracking loop.

The principal interference susceptibility of a maser preamplifier is due to strong signals near the maser passband or the maser idle frequencies. Strong interfering signals influence the operation of a maser by saturating the pre-amplifier and driving one or more of its components into non-linear regions of operation. This results in gain compression and the generation of harmonics, spurious signals, and intermodulation products.

The potential for harmful interference resulting from unwanted emissions is an issue that affects all services. One form of potentially harmful interference that can be of particular concern for spaceborne emitters is spurious emissions. Spurious emissions are due to signal harmonics generated by transmitter intermodulation

effects. They are a particular concern because of the large portions of spectrum that can be affected by such emissions and the fact that transmitter adjustment or modifications are normally impossible after launch of the spacecraft.

A consequence of using sensitive spacecraft receivers, especially those used for deep-space, is their susceptibility to any type of interference whether it is generated within or outside of the allocated space research bands. An emitter in a frequency band adjacent to an allocated space research band may produce interference levels in the space research band that exceed the protection criteria. Guardbands and band edge filtering of the transmitted and received signal may be used to limit interference from out-of-band emissions. Typically, however, there are no provisions in the ITU RR providing for guardbands.

4.2   Protection criteria for the space research service

Space research protection criteria are well documented in the following ITU-R Recommendations:

–   Recommendation ITU-R SA.363 – Space operation systems. Frequencies, bandwidths and protection criteria

–   Recommendation ITU-R SA.609 – Protection criteria for telecommunication links for manned and unmanned near-Earth research satellites

–   Recommendation ITU-R SA.1155 – Protection criteria related to the operation of data relay satellite systems

–   Recommendation ITU-R SA.1157 – Protection criteria for deep-space research

–   Recommendation ITU-R SA.1396 – Protection criteria for the space research service in the 37-38 and 40-40.5 GHz bands

–   Recommendation ITU-R SA.1743 – Maximum allowable degradation to radio-communication links of the space research and space operation services arising from interference from emissions and radiations from other radio sources

These Recommendations are to be consulted in any interference/sharing study.

4.3   Sharing considerations for the space research service

Sharing between other services and the space research service is complex for many reasons. The primary reason is the dynamic nature of the interference environment. The motion of spacecraft relative to each other and the surface of the Earth leads to constantly changing factors such as antenna coupling and received power levels. Relative motions and consequential changes in communication links range from small to large and can have a significant impact on the level, the duration, and the probability of interference.

Secondly, the near-Earth and deep-space communication system characteristics vary widely and depend on a number of factors such as mission requirements, orbital characteristics, spacecraft sophistication, and budgetary constraints.

For near-Earth missions, the distribution and concentration of terrestrial emitters are an important factor in interference considerations and, depending on spacecraft altitude and orbital characteristics, may have a very pronounced effect in the sharing environment. The consequence of these considerations is that interference and sharing determinations involving near-Earth space research missions are typically based on statistical analyses that take into account the dynamics of moving spacecraft. Sophisticated computer programs capable of handling a multiplicity of variables and communication characteristics are currently used by the space research service community to accurately assess the potential for sharing the use of frequency bands with other services.

Recommendation ITU-R SA.1016 addresses the feasibility of frequency sharing between deep-space research stations and stations of other services.

A number of ITU-R Recommendations exist to define the sharing scenario near 2 GHz. Recommendation ITU-R SA.1273 establishes the maximum power flux-density limits in the band 2 200-2 290 MHz produced at the surface of the Earth by emissions from a space station operating in the space-to-Earth direction, including the DRS to LEO spacecraft links. The companion Recommendation ITU-R SA.1274 recommends

an aggregate interference power density level to protect DRS to LEO spacecraft links. Provisions for sharing the 2 GHz bands between DRS to LEO spacecraft links and mobile systems are documented in Recommendation ITU-R SA.1154. Recommendation ITU-R F.1248 sets forth practical limits on the effective isotropic radiated power and spectral density radiated by fixed service stations in the direction of DRS, and Recommendation ITU-R SA.1275 identifies DRS orbital locations to be protected from fixed service emissions in this band.

In the band 25.25-27.5 GHz, interference from space research LEO spacecraft into GSO-FSS satellites is not likely since the e.i.r.p. from the space research spacecraft are significantly lower than that of transmitting FSS earth stations. Interference into a DRS from FSS earth stations is feasible. As a DRS tracks a spacecraft, coupling between the DRS and the FSS earth station antenna can result in harmful interference to the DRS receiver. Although antenna beams at this frequency are relatively narrow, interference that may occur with earth stations located at the limb of the Earth as seen by a DRS, can last for a relatively long period of time. Recommendation ITU-R F.1249 sets forth practical limits on the e.i.r.p. and spectral density radiated by fixed service stations in the direction of DRS. Recommendation ITU-R SA.1276 identifies the DRS orbital locations that need to be protected from interference.

Recommendation ITU-R SA.1862 addresses guidelines for efficient use of the 25.5-27.0 GHz band, while Recommendation ITU-R SA.1626 addresses the feasibility of sharing in the 14.8-15.0 GHz band. Recommendation ITU-R SA.1810 addresses guidelines for Earth exploration-satellites operating in the band 8 025-8 400 MHz, while Recommendation ITU-R SA.1629 addresses the sharing of the command links in the band 257-262 MHz.

4.3.1 Interference from space research earth stations

Interference from space research earth stations into non-GSO spacecraft is a dynamic situation dependent upon time-varying characteristics. These characteristics include the time a victim spacecraft spends in the beam of an earth station antenna, the pointing characteristics of the transmitting Earth station as it tracks and communicates with a space research spacecraft, and, if directional antennas are employed by the victim spacecraft, the spacecraft antenna pointing characteristics. Factors, such as operational frequency, antenna type, size, beamwidth, etc., are additional considerations used to determine the duration and level of interference power into the victim spacecraft receiver.

Interference from space research earth stations into terrestrial fixed and mobile stations are controlled by provisions in the RR. Article **9** defines the procedure for effecting coordination with or obtaining agreement of other administrations and Article **21** addresses terrestrial and space services sharing frequency bands above 1 GHz. Appendix **7** provides the method for the determination of the coordination area around an earth station in frequency bands between 100 MHz and 105 GHz shared between space and terrestrial radiocommunication services.

Appropriate GSO orbital spacing, narrow antenna beamwidths and pointing directions mitigate any interference between DRS Earth-to-space links and other GSO satellites. Appendix **8** of the RR gives the method of calculation for determining if coordination is required between geostationary satellite networks sharing the same frequency band. Article **21** of the RR constrains the e.i.r.p. levels for earth stations, including those used by DRS systems, which protects the fixed and mobile systems.

4.3.2 Interference into space research spacecraft

Space research spacecraft operating in low Earth orbit may not generally receive interference from GSO satellites in the fixed- or mobile-satellite services due to the shorter distance between the space research spacecraft and its earth station compared to the much larger distance between the space research spacecraft and GSO satellite, and due to the higher e.i.r.p. of the space research earth station, and directivity of all the antennas involved. There exists, however, a potential for such space research spacecraft to receive interference from non-GSO satellite systems in the fixed- or mobile-satellite services. Space research spacecraft operating in the medium earth orbit or higher which are closer to the GSO satellites may however receive unacceptable interference from fixed- or mobile-satellite services satellites. The number and proximity of transmitting satellites may together constitute a source of interference to a receiving space research spacecraft.

For space research spacecraft operating far beyond the geosynchronous orbit or in the deep-space distances, no interference is expected from satellites in the fixed- or mobile-satellite services.

Provisions of Articles **9** and **21** of the RR control interference from earth stations into a space research spacecraft. The potential for interference from fixed systems does exist. Taking into account the dynamics of the interference situation, the deployment of fixed systems, and pointing restrictions applicable to transmitting earth stations, the level of interference should be minimal. The increase in the use of fixed service systems for point-to-multipoint applications may have a significant impact on sharing with the space research service.

4.3.3   Interference from space research spacecraft

Interference into terrestrial stations is generally controlled by the development of appropriate power flux-density limits applicable to space research spacecraft. These power flux-density limits are documented in Article **21** of the RR. In the 137-138 MHz, 143.6-143.65 MHz and 400.15-401 MHz bands, there are no power flux-density limits. Space research spacecraft transmit using omnidirectional antennas to receiving earth station antennas that are relatively large and have a higher gain than the antennas employed by the fixed and mobile services. The differential gain in the respective antennas and the proximity of the fixed/mobile transmit and receive antennas to each other, minimizes the potential of interference that may occur during any space research transmissions, particularly at the limb of the Earth.

The level and duration of any interference into earth stations of the meteorological-satellite service is significantly reduced through their use of large antennas, their tracking requirements, and spatial deployment of both the space research and the meteorological-satellite earth stations.

No interference, due to side-lobe coupling of antennas, is expected from DRS space-to-Earth links into GSO fixed-satellite service (FSS) system (Earth-to-space) links. GSO-FSS satellites located anti-podal to a DRS will also not experience harmful interference due to distance and antenna coupling factors. Factors such as narrow antenna beams and coupling, proximity of a mobile satellite to its transmitting terrestrial station, and the orbital dynamic of the interference situation, will result in little to no harmful interference into the mobile satellites from DRS space-to-Earth links.

Interference into FSS earth stations from DRS space-to-Earth links is mitigated through factors such as appropriate spatial separation, side-lobe coupling of large earth station antennas and polarization. Coordination, if required, will follow the method provided in Appendix **8** of the RR. The dynamics associated with mobile-satellite earth stations requirements for tracking LEO spacecraft will also mitigate interference from DRS space-to-Earth emissions.

4.3.4   Interference into space research earth stations

Interference into space research earth stations from mobile-satellite service operations in the band 137-138 MHz are subject to coordination under Article **9** of the RR. Below 1 GHz appropriate deployment and site shielding may be used to protect space research earth stations sites and to minimize the need for coordination with fixed and mobile emitters. Above 1 GHz, Article **21** of the RR applies. The method for the determination of the coordination area around an earth station in frequency bands between 100 MHz and 105 GHz shared between space and terrestrial radiocommunication services is given in Appendix **7** of the RR.

Interference from LEO mobile satellites may be a source of interference to DRS space-to-Earth links due to their close proximity to the surface of the Earth, the density of their systems and the number of systems that are likely to operate within the band. The potential for interference from fixed and mobile stations does exist if the DRS earth station protection criteria in Recommendation ITU-R SA.1155 are exceeded. For these cases, coordination may be necessary as described in Appendix **7** of the RR.

4.3.5   ITU unwanted emissions limits

The ITU-R defines unwanted emissions in two separate regions. The region just outside the necessary bandwidth is the out-of-band region; the region farther out is the region of spurious emissions. Recommendation ITU-R SM.1539 defines the boundary region. In general, the boundary is 250% of the necessary bandwidth, but there are some exceptions.

Radio Regulations No. **3.8** states that, in regards to out-of-band emissions, transmitting stations should, to the maximum extent possible, satisfy the most recent ITU-R Recommendation. The out-of-band emission mask for space services is defined in Annex 5 of Recommendation ITU-R SM.1541. However, there is currently no ITU out-of-band emission mask applicable for space services operating space-to-space links.

Radio Regulations No. **3.7** states that transmitting stations shall conform to the maximum permitted spurious emission power levels specified in Appendix **3** of the RR**.** Table II of Appendix **3** shows that for space services, the peak attenuation in the spurious emission region is $43 + 10 \log P$, or 60 dBc, whichever is less stringent. P is defined to be the power (in Watts) supplied to the antenna transmission line.

ATTACHMENT 1

ITU-R Recommendations and Reports relevant to the space research service

Recommendations ITU-R

SA.363	Space operation systems. Frequencies, bandwidths and protection criteria
SA.364	Preferred frequencies and bandwidths for manned and unmanned near-Earth research satellites
SA.509	Space research earth station and radio astronomy reference antenna radiation pattern for use in interference calculations, including coordination procedures, for frequencies less than 30 GHz
SA.510	Feasibility of frequency sharing between the space research service and other services in bands near 14 and 15 GHz – Potential interference from data relay satellite systems
SA.609	Protection criteria for telecommunication links for manned and unmanned near-Earth research satellites
SA.1014	Telecommunication requirements for manned and unmanned deep-space research
SA.1015	Bandwidth requirements for deep-space research
SA.1016	Sharing considerations relating to deep-space research
SA.1018	Hypothetical reference system for systems comprising data relay satellites in the geostationary orbit and user spacecraft in low Earth-orbits
SA.1019	Preferred frequency bands and transmission directions for data relay satellite systems
SA.1154	Provisions to protect the space research (SR), space operations (SO) and Earth-exploration satellite services (EES) and to facilitate sharing with the mobile service in the 2 025-2 110 and 2 200-2 290 MHz bands
SA.1155	Protection criteria related to the operation of data relay satellite systems
SA.1157	Protection criteria for deep-space research
SA.1274	Criteria for data relay satellite networks to facilitate sharing with systems in the fixed service in the bands 2 025-2 110 MHz and 2 200-2 290 MHz
SA.1275	Orbital locations of data relay satellites to be protected from the emissions of fixed service systems operating in the band 2 200-2 290 MHz
SA.1276	Orbital locations of data relay satellites to be protected from the emissions of fixed service systems operating in the band 25.25-27.5 GHz
SA.1344	Preferred frequency bands and bandwidths for the transmission of space VLBI data within existing space research service (SRS) allocations
SA.1345	Methods for predicting radiation patterns of large antennas used for space research and radio astronomy
SA.1396	Protection criteria for the space research service in the 37-38 and 40-40.5 GHz bands
SA.1414	Characteristics of data relay satellite systems

SA.1415	Sharing between inter-satellite service systems in the frequency band 25.25-27.5 GHz
RS.1449	Feasibility of sharing between the fixed-satellite service (FSS) (space-to-Earth) and the Earth exploration-satellite (passive) and space research (passive) services in the band 18.6-18.8 GHz
SA.1626	Feasibility of sharing between the space research service (space-to-Earth) and the fixed and mobile services in the band 14.8-15.35 GHz
SA.1629	Sharing between command links in the space research and space operation services with the fixed, mobile and mobile-satellite services in the frequency band 257-262 MHz
SA.1742	Technical and operational characteristics of interplanetary and deep-space systems operating in the space-to-Earth direction around 283 THz
SA.1743	Maximum allowable degradation to radiocommunication links of the space research and space operation services arising from interference from emissions and radiations from other radio sources
SA.1805	Technical and operational characteristics of space-to-space telecommunication systems operating around 354 THz and 366 THz
SA.1810	System design guidelines for Earth exploration-satellites operating in the band 8 025-8 400 MHz
SA.1811	Reference antenna patterns of large-aperture space research service earth stations to be used for compatibility analyses involving a large number of distributed interference entries in the bands 31.8-32.3 GHz and 37.0-38.0 GHz
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)
SA.1863	Radiocommunications used for emergency in manned space flight
SA.1882	Technical and operational characteristics of space research service (Earth-to-space) systems for use in the 22.55-23.15 GHz band

Reports ITU-R

SA.2065	Protection of the space VLBI telemetry link
SA.2066	Means of calculating low-orbit satellite visibility statistics
SA.2067	Use of the 13.75 to 14.0 GHz band by the space research service and the fixed-satellite service
SA.2098	Mathematical gain models of large-aperture space research service earth station antennas for compatibility analysis involving a large number of distributed interference sources
SA.2132	Telecommunication characteristics and requirements for space VLBI systems
SA.2162	Sharing conditions between space research service extra vehicular activities (EVA) links and fixed and mobile service links in the 410-420 MHz band
SA.2166	Examples of radiation patterns of large antennas used for space research and radio astronomy
SA.2167	Factors affecting the choice of frequency bands for space research service deep-space (space-to-Earth) telecommunication links
SA.2177	Selection of frequency bands in the 1-120 GHz range for deep-space research
SA.2183	Method for calculating link performance in the space research service
SA.2190	Study on compatibility between the mobile service (aeronautical) and the space research service (space-to-Earth) in the frequency band 37-38 GHz
SA.2191	Spectrum requirements for future SRS missions operating under a potential new SRS allocation in the band 22.55-23.15 GHz
SA.2192	Compatibility between the space research service (Earth-to-space) and the non-GSO-to-non-GSO systems on the inter-satellite service in the band 22.55-23.55 GHz
SA.2193	Compatibility between the space research service (Earth-to-space) and the systems in the fixed, mobile and inter-satellite service in the band 22.55-23.15 GHz

ATTACHMENT 2

Table of SRS uses and corresponding pfd limits

Frequency		Use SRS = Non-specific s-E = space-to-Earth E-s = Earth-to-space s-s = space-to-space ds = deep-space	Power flux-density limit for angles of arrival (θ) Above the horizontal plane (dBW/m²)[1]			Reference bandwidth
			$0º \le θ \le 5º$	$5º < θ \le 25º$	$25º < θ \le 90º$	
2 501-2 502	kHz	SRS				
5 003-5 005	kHz	SRS				
10 003-10 005	kHz	SRS				
15 005-15 010	kHz	SRS				
18 052-18 068	kHz	SRS				
19 990-19 995	kHz	SRS				
25 005-25 010	kHz	SRS				
30.005-30.01	MHz	SRS				
39.986-40.02	MHz	SRS				
40.98-41.015	MHz	SRS				
137-138	MHz	s-E				
138-143.6	MHz	s-E				
143.6-143.65	MHz	s-E				
143.65-144	MHz	s-E				
400.15-401	MHz	s-E				
410-420	MHz	s-s				
1 215-1 300	MHz	active sensing				
2 025-2 110	MHz	E-s. s-s	−154	$−154 + 0.5\,(θ − 5)$	−144	4 kHz
2 110-2 120	MHz	ds, E-s				
2 200-2 290	MHz	s-E, s-s	−154	$−154 + 0.5\,(θ − 5)$	−144	4 kHz
2 290-2 300	MHz	ds, s-E	−154	$−154 + 0.5\,(θ − 5)$	−144	4 kHz
3 100-3 300	MHz	active sensing				
5 250-5 570	MHz	SRS				
5 650-5 670	MHz	ds				
5 670-5 725	MHz	ds	−152	$−152 + 0.5\,(θ − 5)$	−142	4 kHz
7 145-7 190	MHz	ds, E-s				
7 190-7 235	MHz	E-s				
8 400-8 450	MHz	ds, s-E	−150	$−150 + 0.5\,(θ − 5)$	−140	4 kHz
8 450-8 500	MHz	s-E	−150	$−150 + 0.5\,(θ − 5)$	−140	4 kHz
8 550-8 650	MHz	active sensing				
9 300-9 800	MHz	active sensing				
9 800-9 900	MHz	active sensing				
12.75-13.25	GHz	ds, s-E				
13.25-13.4	GHz	active sensing				
13.4-14.3	GHz	active sensing				
14.4-14.47	GHz	s-E				
14.5-15.35	GHz	SRS				
16.6-17.1	GHz	ds, E-s				
17.2-17.3	GHz	active sensing				

Frequency		Use SRS = Non-specific s-E = space-to-Earth E-s = Earth-to-space s-s = space-to-space ds = deep-space	Power flux-density limit for angles of arrival (θ) Above the horizontal plane (dBW/m^2) [1]			Reference bandwidth
			0º ≤ θ ≤ 5º	5º < θ ≤ 25º	25º < θ ≤ 90º	
22.55-23.55	GHz	s-s	−115	−115 + 0.5 (θ − 5)	−105	1 MHz
22.55-23.15	GHz	E-s				
25.25-27.5	GHz	s-s	−115	−115 + 0.5 (θ − 5)	−105	1 MHz
25.5-27	GHz	s-E	−115	−115 + 0.5 (θ − 5)	−105	1 MHz
31-31.3	GHz	SRS	−115	−115 + 0.5 (θ − 5)	−105	1 MHz
31.8-32.3	GHz	ds, s-E	−120	−120 + 0.75 (θ − 5)	−105	1 MHz
34.2-34.7	GHz	ds, E-s				
34.7-35.2	GHz	SRS	−115	−115 + 0.5 (θ − 5)	−105	1 MHz
35.5-36	GHz	active sensing				
37-38	GHz	s-E, NGSO	−120	−120 + 0.75 (θ − 5)	−105	1 MHz
37-38[2]	GHz	ds, s-E, NGSO	−115	−115 + 0.5 (θ − 5)	−105	1 MHz
37-38	GHz	s-E, GSO	−125	−125 + (θ − 5)	−105	1 MHz
40-40.5	GHz	E-s				
65-66	GHz	SRS				
74-84	GHz	s-E				
94-94.1	GHz	active sensing				

[1] Blank cell means the value is not available.

[2] By ITU RR Footnote **21.16.10**, this relaxed pfd limit applies to the launch and near-Earth operational phases of deep-space missions, which are part of the non-geostationary SRS systems.

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International Telecommunication Union
Sales and Marketing Division
Place des Nations
CH-1211 Geneva 20
Switzerland
Fax: +41 22 730 5194
Tel.: +41 22 730 6141
E-mail: sales@itu.int
Web: www.itu.int/publications