

# Handbook on Space research communication

Edition of 2026





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***Edition of 2026***

**Radiocommunication Bureau**



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## **Preface**

The Handbook on space research communication has been developed by experts of Working Party (WP) 7B of Radiocommunication Study Group 7 (Science services). The original version was created under the chairmanship of Mr S. Taylor (United States of America), Chair, Working Party 7B. The 2014 version, under the chairmanship of Mr B. Kaufman (United States of America), Chair, 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 latest version, under the chairmanship of Ms C. Sham (United States of America), Chair, Working Group 7B, includes updates to reflect advancements in space and ground segments, deep space optical communication, and new SRS applications. Additionally, a new attachment containing examples of space exploration missions is included to illustrate the use of the systems, principles and techniques discussed in this Handbook.

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 seven chapters and three attachments, 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. The material is aligned with the regulatory and technical of the documentation of ITU Radiocommunication Sector, including applicable Recommendations and Reports.

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

Mario Maniewicz

Director, Radiocommunication Bureau

## Foreword

Radiocommunication Study Group 7 (Science Services) was created through a structure reorganization in 1990 at the Düsseldorf CCIR Plenary Assembly. Many of the Study Group 7 activities 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 four Working Parties that address technical issues related to specific disciplines in science services. Space research service (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.

Since the last publication of this Handbook in 2014, tremendous advances in numerous scientific and technical disciplines have benefited mankind and furthered our knowledge and understanding of the universe including robotic spacecraft exploration to the planets and beyond the limits of our solar system, technology demonstrations for the exploration of the moon, continuous human presence in low-Earth orbit space stations. Now, many more administrations have active space programs, and the provision of enhanced space communications by means of data relay satellites and joint missions to mature advanced communications technologies for space applications. There is growing involvement in robotic exploration of the Moon and Mars by many space agencies with industry partners, with the intent of eventually sending humans to Mars for exploration and discovery.

Continued improvements and achievements in space research 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.

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

Commensurate with increases in space research activities is the need for higher data rates to accommodate more complex missions. 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.

The Handbook is written to provide the reader a general understanding of the space research service including basic technical information to support different space research programmes, missions and activities. It is written primarily for administrators and agency personnel involved in spectrum management, but it can be of benefit to students and others who are interested in acquiring an understanding on missions under space research service.

Markus Dries  
Chair, Study Group 7

## **Acknowledgement**

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**Acronyms and abbreviations**

ATV	Automatic transfer vehicle
BER	Bit error rate
BPSK	Binary phase shift keying
BRTS	Bilateration ranging transponder system
CCIR	International Radio Consultative Committee
DOR	Differential one-way ranging
DRS	Data relay satellites
e.i.r.p.	effective/equivalent isotropically radiated power
EVA	Extra-vehicular activity
FDM	Frequency division multiplexing
FSS	Fixed-satellite service
GMSK	Gaussian minimum shift keying
GSO	Geostationary orbit
HEMT	High electron mobility transistor
HEO	Highly elliptical orbit / high earth orbit
IF	Intermediate frequency
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
L1	First Lagrange point
L2	Second Lagrange point
LEO	low-earth orbit
LNA	Low noise amplifier
MASER	Microwave amplification by stimulated emission of radiation
MEO	medium-Earth orbit
pdf	power flux-density
PM	Phase modulation
PPM	Pulse position modulation
PSK	Phase shift keying
QPSK	Quadrature phase shift keying
RF	Radio frequency
RR	Radio Regulations
RS	Reed-Solomon
SRS	Space research service
TDM	Time division multiplexing
UT1	Universal time
VLBI	Very long baseline interferometry

## 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. Some examples of space exploration missions and their objectives are given in Attachment 3. The common objective of these missions is to observe, investigate, gather and return science data for humans to understand the universe around us.

#### 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 physics* 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.

*Planetary systems research* involves studying planets, their moons, asteroids, and comets to gain knowledge of the origin and evolution of our solar system. Extensive information on the planets and their moons is provided by spacecraft, probes and planetary landers.

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 humans 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 the deep-space regions include human and robotic missions, communication networks on the surface of the Earth, and communication networks in geosynchronous orbit or beyond. Human missions involve human exploration, transportation of crew and personnel to scientific outposts, conducting experiments

and research from locations in space. Robotic missions involve using robotic spacecraft for collection of physical samples, supplying or servicing research spacecraft, and using spacecraft for collection of remote sensing and observational data.

Space research missions targeted for objectives further than  $2 \times 10^6$  km from the Earth are referred to as 'deep-space' missions. Conversely, missions closer than  $2 \times 10^6$  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 human missions and robotic missions, the return to Earth and landing operations. To successfully complete these operations, each phase requires specialized communication and tracking systems. 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 human missions, the communication functions include audio 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. In addition, it is becoming more common to have radio communication between the landers and robots on the surface of planets and moons, and between landers and vehicles flying in the atmosphere.

## 1.2 Space research mission characteristics

The space research mission characteristics mainly include the durations, orbits and types of missions. Duration of missions is usually specified in terms of flight time and actual mission time. Mission types and satellite orbits used by the missions vary depending on their specific research objectives and the location of these objectives. The orbit types include low-Earth orbits, polar orbits, sun-synchronous orbits, elliptical orbits, geostationary orbits, or halo orbits. The mission types include near-Earth missions, deep-space missions, transfer of cargo or personnel missions, orbiters, landers, lunar or planetary missions, or data relay missions. Mission characteristics are further discussed in the following sections.

### 1.2.1 Space research mission durations

The duration of a space research mission essentially consists of the flight time and the actual mission time. The flight time is defined as the time from launch to reaching final destination of the mission. The actual mission time is defined as the time required for experimentation, data acquisition, and completion of mission objectives. For sample return and human 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 human 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  $1.58 \times 10^9$  km distant, may have a flight time of six to seven 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, but they are usually extended to operate many more years. The durations for robotic and human 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 km 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 periapsis and a large apoapsis. 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 Earth 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 human 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 lander 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), the Japanese Aerospace Exploration Agency's H-II transfer vehicle "KOUNOTORI" (HTV) and HTV-X, SpaceX's Dragon, and Orbital Science's Cygnus vehicles 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 human 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 (see Chapter 5 for more technical details).

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 fulltime 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 with 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  $2 \times 10^6$  km from the Earth. Extreme distances characterize deep-space missions, with some current missions in excess of 23 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

Space research systems have telecommunication requirements that are met using equipment and facilities on Earth and in space. Earth segment includes the locations of earth stations and the antennas used depending on the mission types. Space segment includes the actual satellites and the spacecraft, their locations in space, and the various antennas that are used during the mission lifetime. The characteristics of the Earth segment and the space segment are further discussed in detail in the following sections.

#### 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 at earth stations for near-Earth space research 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 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 radiation pattern can be found in Recommendation ITU-R SA.509, while Recommendation ITU-R SA.1811 gives the patterns to be used for compatibility analysis in the 32-GHz and 37-GHz bands. Methods for predicting radiation patterns of large antennas are found in Report ITU-R SA.2098 and Report ITU-R SA.2401.

The smallest signal a space research receiver can detect is limited by the ambient noise generated in the receiver and the radio noise 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 isotropically 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, 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 1.1 and 1.2.

TABLE 1.1

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

Frequency range		Noise temperature (K)
~2	GHz	150
~8	GHz	120
10-11	GHz	160
13-15	GHz	300
18-26	GHz	200
37-38	GHz	200

TABLE 1.2

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

Frequency		Noise temperature (K)	G/T (dB/K)
2 290-2 300	MHz	21-25	50
8 400-8 450	MHz	27-65	50-59.5
12.75-13.25	GHz	29-35	62
31.8-32.3	GHz	61-83	65.2

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 isotropically 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 121 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. It needs to be noted, that SRS spacecraft often operate more than one antenna with different gains for the different orbital phases of the mission: Low-gain to medium-gain antennas for launch and transfer, and medium-gain to high-gain antennas for transfer and nominal mission operation, depending on the spacecraft distance to Earth.

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 envelope of the antenna gain pattern.

$$\begin{aligned}
 G(\varphi) &= G_m - 3(\varphi/\varphi_0)^2 && \text{for} && 0 \leq \varphi \leq 2.58 \varphi_0 \\
 G(\varphi) &= G_m - 20 && \text{for} && 2.58 \varphi_0 < \varphi \leq 6.32 \varphi_0 \\
 G(\varphi) &= G_m - 25 \log_{10}(\varphi/\varphi_0) && \text{for} && 6.32 \varphi_0 < \varphi \leq \varphi_1 \\
 G(\varphi) &= 0 && \text{for} && \varphi_1 < \varphi
 \end{aligned}$$

where:

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

$G_m$ : maximum gain in the main lobe (dBi)

$\varphi_0$ :  $0.5 \sqrt{27000/(10^{G_m/10})}$  degrees, (one half the 3-dB beamwidth)

$\varphi_1 = \varphi_0 10^{G_m/25}$  degrees, (value of  $\varphi$  when  $G(\varphi)$  in the third equation is equal to 0 dBi).

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 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 1.3 and 1.4.

TABLE 1.3

**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	400-800
10-20	GHz	800-1 200
> 20	GHz	1 200-1 500

TABLE 1.4

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

Frequency range		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 (see Table A2.2) 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 pfd limits.

Transmitter power ranges for DRS systems are found in the Tables contained in the Annex to Recommendation ITU-R SA.1414. Near-Earth space research spacecraft transmit 2-15 W, and deep-space spacecraft transmit 5-100 W, with lower transmit powers during early orbital phases.

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 since 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 of command, telemetry and tracking, are known as the space operation functions. Space research missions use their allocated frequency 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 brief discussion of the space operation functions and the implementations of space research communication and tracking systems are given in this section. Further deep-space technical discussions can be found in Recommendation ITU-R SA.1014.

#### **2.1 Functions**

The primary functions of spacecraft communication are the transmission and reception of commands, engineering telemetry, scientific data, and tracking data. Additionally, it also includes the transmission and reception of radio science data. These space operation functions are discussed briefly in the following sections.

##### **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 human 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

The design and implementation of the space communication links depend heavily on the mission objectives. The communication links have to meet the reliability and the bit error rate requirements of the missions, and achieve enough link margins for safe operations. This involves careful planning of data rates that are possible within the allocated bandwidths and available transmit powers. The considerations for a successful communication link also include frequency turnaround ratios, multiplexing, bit error correction and pseudo-random noise (PN) coding, and modulation techniques. For a successful mission, the transmitted carrier frequencies have to be acquired and tracked, engineering and scientific data have to be extracted, and the position of the spacecraft have to be determined and tracked with precision. The more detailed discussions of these topics are given in the following sections.

### 2.2.1 Reliability, bit error rate 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. Human 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 rate (BER) less than  $1 \times 10^{-5}$  (less than  $1 \times 10^{-6}$  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. Human 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.

$$Tx\text{-frequency} = Rx\text{-frequency} \times \text{Turnaround-ratio}$$

Space research turnaround ratios depend on the frequency band used as shown in Table 2.1.

TABLE 2.1

Space research turnaround ratios

Frequency band (GHz / GHz)	Turnaround ratio (Downlink / Uplink)
2 / 2	240 / 221
8 / 7	880 / 749
15 / 13	1 600 / 1 469
32 / 34	3 328 / 3 599 3 344 / 3 599 3 360 / 3 599

#### 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 biphase modulate the command channel IF carrier. If ranging is required, a long PN code biphase modulates the ranging channel IF carrier. The ranging channel is then combined to the command channel in radio frequency 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 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, human 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 to 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  $1/5$  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 human 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 and 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 GHz 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 GHz 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 K to 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 ranges from 600 K 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 GHz 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 radio-wave 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 human 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 2290-2300 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 list of frequency bands allocated to SRS uses and corresponding pfd limits in transmit bands are 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 and 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 be long-lasting. 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 or HEMT low-noise preamplifier (LNA) is due to strong signals near the LNA passband or near the idle frequencies. Strong interfering signals influence the operation of an LNA 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
- Recommendation ITU-R SA.2044 – Protection criteria for non-GSO data collection platforms in the band 401-403 MHz

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. This effect also needs to be considered for critical mission phases of deep space missions, such as the early orbit phase or Earth fly-bys with only small distances to Earth. 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. Recommendation ITU-R SA.2079 addresses frequency sharing between SRS and FSS (space-to-Earth) systems in the 37.5-38 GHz band.

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 and beamwidth 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 pfd 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.

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.

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. Methodologies for calculating coordination areas around EESS and SRS earth stations to avoid harmful interference from IMT systems in the frequency bands 25.5-27 GHz and 37-38 GHz are covered in Recommendation ITU-R SA.2142. Protection of SRS earth stations from mobile (aircraft) stations in the 2 200-2 290 MHz band is covered in Recommendation ITU-R SA.2078.

#### 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 2.5 times the necessary bandwidth, but there are some exceptions.

Radio Regulations No. 3.8 states that, in regard 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 to 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.



## CHAPTER 5

**Example space research service application: Space VLBI systems**

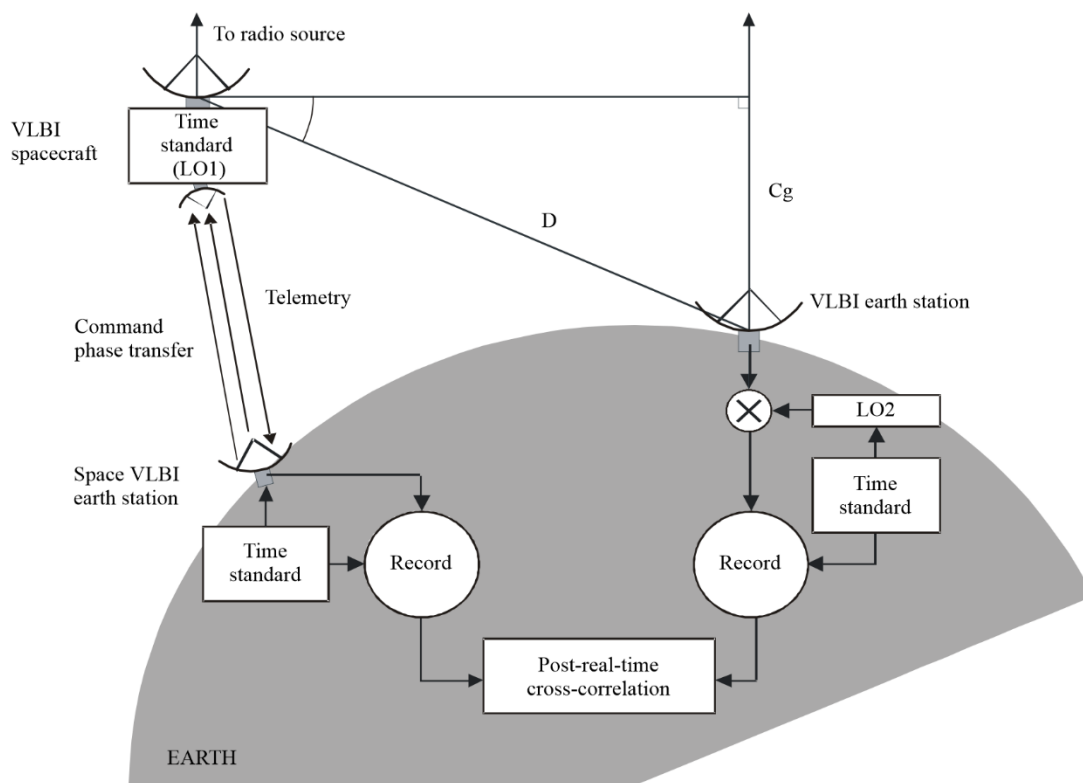
Very long baseline interferometry (VLBI) allows experimenters to observe radio sources with angular resolutions that cannot be approached by other methods. Observations of distant radio sources with two or more VLBI stations can be combined to study the structure and positions of extra-galactic radio sources, the geodynamical characteristics of the Earth, and the Moon's libration and tidal responses. It is also used to determine orientation of the solar system with respect to the extra-galactic inertial frame, the vector separation between antenna sites, and to provide navigation and tracking of spacecraft.

**5.1 Description of the Space VLBI system**

A simple VLBI system is composed of two VLBI earth stations, whose antennas point to the same radio source for a planned observation. The resulting observed frequency spectrum is translated down to a lower frequency, whose amplitude and phase are maintained by using highly stable frequency reference local oscillators (LO). The observed spectra at each antenna are recorded independently and are cross-correlated to obtain the brightness map of the observed source. In the case of Space VLBI, one of the antennas used to observe the radio source is space-borne and the observed spectrum needs to be transmitted to the Space VLBI earth station and be recorded (see Fig. 5.1).

FIGURE 5.1

**Outline of a typical space VLBI experiment, in which a spaceborne antenna is used in parallel with one or more VLBI observing stations on the ground**



## 5.2 Telecommunication links for Space VLBI

The telecommunication links of the Space VLBI system are represented in Fig. 5.1 by the lines between the Space VLBI spacecraft telecommunication antenna and the Space VLBI earth station. These radio links are described below.

- a) *Earth-to-space telecommand link*: This radio link is used for reliable transmission of telecommands, which is required for the operation of the spacecraft and also to correct the possible malfunctions of spacecraft behaviour.
- b) *Space-to-Earth telemetry link*: Once the spacecraft observes the radio source over a selected frequency bandwidth, it first stores the observed spectrum as science data, and then transmits the data to the Space VLBI earth station using this s-E telemetry link. At the earth station, the received science data is recorded and cross-correlated with the same spectrum observed by the other VLBI earth stations.
- c) *Earth-to-space phase transfer link*: This radio link is used for time and frequency synchronization. In VLBI, accurate knowledge of the time, signal frequency, and signal phase is needed in the post processing cross-correlation of the recorded signals. This required accuracy is met by using highly stable reference oscillators (atomic clocks) at every station and by utilizing the Global Positioning System (GPS). At present the E-s phase-transfer link is used to impart the required time and phase reference to the clock and local oscillators on-board the spacecraft, but in the future the Space VLBI spacecraft itself may carry a space-qualified atomic clock. Even then, the E-s phase transfer link will still be needed for time synchronization, since the distant Space VLBI station may not be able to utilize the GPS system for time synchronization.
- d) *Space-to-Earth phase transfer link*: This radio link is a coherent frequency translation of the E-s phase transfer link to calibrate the phase errors introduced in the E-s phase transfer link due to various physical phenomena. The s-E phase transfer link may be dedicated only to the phase transfer operation or may be combined with the s-E telemetry link for science data to transfer the observed spectra from the spacecraft.

## 5.3 Technical characteristics

The following subsections give a brief introduction to the cross-correlation function used in VLBI post processing, and a detailed characterization of the Space VLBI telemetry link for science data and the phase-transfer link for time and frequency synchronization.

### 5.3.1 VLBI cross correlation function

The basic observables in radio interferometry are the amplitudes and relative phases of the two observed spectra of the same radio source. This cross-correlation process involves averaging the product of one recorded signal multiplied by the shifted version of the other recorded signal. It is usually performed in non-real time and is expressed as

$$R_{xy}(\epsilon) = \langle x(t) \cdot y(t - \epsilon) \rangle \quad (5.1)$$

where  $R_{xy}$  is the cross-correlation function,  $x(t)$  and  $y(t)$  are the recorded signals at sites 1 and 2,  $\epsilon$  is the wave front time delay, and  $\langle \rangle$  is the estimated mean value of the result over time. In the cross-correlation function, the pre-recorded signals will be contaminated with system noises of the receiving stations. For each receiving station, the received spectral density ( $\rho_{1,2}^2$ ) of the observed signal and system noise ( $\eta_{1,2}^2$ ) can be defined as follows:

$$\rho_1^2 = \frac{1}{2} \sigma_1^2 A_1, \quad \rho_2^2 = \frac{1}{2} \sigma_2^2 A_2, \quad \eta_1^2 = kT_1, \quad \eta_2^2 = kT_2 \quad (5.2)$$

where  $\sigma_{1,2}^2$  are the spectral flux densities of the observed source at the antennas ( $\text{W}/(\text{Hz} \cdot \text{m}^2)$ ),  $A_{1,2}$  are the effective areas of receive antennas ( $\text{m}^2$ ),  $T_{1,2}$  are the system noise temperatures of the receivers (K), and  $k$  is the Boltzmann's constant ( $\text{W}/(\text{Hz} \cdot \text{K})$ ). Note that the expressions for the received spectral densities have a

factor  $\frac{1}{2}$ , since a receive antenna will only detect the signal power in one polarization direction and not in the other polarization direction. It is known that the cross-correlation signal-to-noise ratio ( $\chi$ ) may be expressed as a function of the received spectral densities and system noises as

$$\chi = \frac{\gamma \rho_1 \rho_2}{\eta_1 \eta_2} \sqrt{2B\tau} \quad (5.3)$$

where  $B$  is the observation bandwidth,  $\tau$  is the integration time of the observation, and  $\gamma$  is the coherence factor of the two observations at two different sites. Coherence factor represents the effects of ionospheric scintillation and rapidly fluctuating ionospheric delay, which introduces phase errors that lowers the amplitude of the cross-correlation. Coherence factor  $\gamma = 1$  means no loss of coherence. The equation above shows that to increase the cross-correlation SNR, it is necessary to use wider observation frequency bandwidths, longer integration times and large antennas with lower system noise temperatures.

### 5.3.2 Telemetry link

The Space VLBI spacecraft receives the frequency spectrum of the radio source contaminated with background noise and system noise present in the observation bandwidth. The observed spectrum at the space-born observatory is transmitted from the space station to the Space VLBI earth station as an analogue signal or it is first digitized and then transmitted to the earth station as a digital signal. At the earth station the received signal is recorded and cross-correlated with the frequency spectrum of the same source observed at the other earth station.

The transmission of the telemetry signal or data through space degrades the signal before it is received by the earth station. In digital transmissions, this degradation increases the bit errors in detecting the information bits. Thus, in both analogue and digital transmissions, there are degradations that affect the final cross-correlation process of the Space VLBI experiment and lower the cross-correlation signal-to-noise ratio (SNR).

### 5.3.3 Cross-correlation SNR degradation due to noise in telemetry link

The transmission of a telemetry signal through space implies some signal degradation when detected at the intended receiver. This link degradation affects the final cross-correlation process of the Space VLBI experiment. For the analogue telemetry link, the cross-correlation SNR ( $\chi_\alpha$ ) that includes the telemetry link losses is given as

$$\chi_\alpha = \sqrt{\frac{\eta_1^2}{\eta_1^2 + \eta_m^2}} \frac{\gamma \rho_1 \rho_2}{\eta_1 \eta_2} \sqrt{2B\tau} \quad (5.4)$$

where  $\eta_m^2$  represents the additional system noise density introduced by the telemetry link and the Earth station receiver. Thus, the cross-correlation SNR degradation for analogue telemetry is given by:

$$\frac{\chi_\alpha}{\chi} = \sqrt{\frac{\eta_1^2}{\eta_1^2 + \eta_m^2}} = \sqrt{\frac{\beta}{1 + \alpha + \beta}}, \quad \text{with } \alpha = \frac{\rho_1^2}{\eta_1^2}, \quad \beta = \frac{\rho_1^2 + \eta_1^2}{\eta_m^2} \quad (5.5)$$

where  $\alpha$  represents the SNR of the observations at station 1 and  $\beta$  represents the SNR of the telemetry link. As expected, if the telemetry link SNR ( $\beta$ ) is large, the cross-correlation SNR degradation approaches one, showing no degradation of the cross-correlation SNR due to the telemetry link.

In digital transmissions, the telemetry link introduces errors in the received information bits, whose probability is quantified by the received symbol SNR. For the digital telemetry link with 1-bit quantization, the cross-correlation SNR is written as

$$\chi_q = (1 - \text{erfc}(\sqrt{\delta}))^2 \frac{\gamma \rho_1 \rho_2}{\pi \eta_1 \eta_2} \sqrt{2B\tau} \quad (5.6)$$

where  $\delta$  is the telemetry link symbol SNR, and  $erfc()$  is the complementary error function. Thus, the cross-correlation SNR degradation for digital telemetry is given by:

$$\frac{\chi_q}{\chi} = (1 - erfc(\sqrt{\delta}))^2 \frac{2}{\pi} \quad (5.7)$$

Note that when telemetry symbol SNR ( $\delta$ ) is large, no bit errors are made and the cross-correlation SNR degradation approaches to  $2/\pi$ , which is the inherent degradation introduced by the quantization of the normally distributed observed source.

### 5.3.4 Required bandwidths for the telemetry link

Phase modulation has been shown to attain optimum performance on satellite telecommunications links. Therefore, binary phase shift keying (BPSK) or quadri-phase shift keying (QPSK) will be considered as the preferred digital modulation schemes. When digitizing the observation bandwidth of  $B$  Hz, the required Nyquist sampling rate will be twice the bandwidth or  $2B$  samples per second. Each observed voltage sample is quantized either at two levels (1-bit representation), four levels (2-bit representation), eight levels (3-bit representation) and so on. Thus, the total telemetering channel symbol rate ( $R_s$ ) and telemetry bandwidth ( $W$ ) follow the equations:

$$R_s = 2B \cdot \log_2(L) = 2Bn, \quad W = 4R_s = 8Bn \quad (5.8)$$

where  $L$  is the total number of quantization levels and  $n$  is the number of bits. For the transmission of BPSK, the required radio-frequency bandwidth of  $W=4R_s$  is taken from Recommendation ITU-R SA.1015 for telemetry losses to be less than 0.3 dB. If QPSK is used, the same bandwidth can accommodate twice the symbol rate with approximately the same performance as the BPSK case, or for the same symbol rate the required bandwidth is half the BPSK bandwidth.

### 5.3.5 Preferred carrier frequencies for the telemetry link

Some existing and planned space VLBI system require a maximum radio frequency transmission bandwidth of 500 MHz. Since these space VLBI systems would require high carrier frequencies with enough allocated bandwidth, the SRS 8-GHz band is not suitable as it is only 50 MHz wide. In the future, space VLBI system will require RF bandwidths of 1 GHz to 10 GHz, which indicate that these systems would need carrier frequencies larger than 20 GHz.

### 5.3.6 Phase-transfer link

The phase transfer link is used to derive a stable on-board frequency reference from a clock on the ground. The frequency of the on-board reference must be precisely known to support science data processing. A prime requirement for an on-board local oscillator of a space VLBI spacecraft is that its frequency/phase stability be nearly as good as that of a VLBI earth station's local oscillator driven by the atomic standard. No space-qualified atomic standard exists today; therefore, the required stability will be transferred to the space VLBI spacecraft via an Earth-to-space radio link. The carrier frequency of this radio link is recovered at the spacecraft to generate the on-board reference frequencies to be used in the radio source observing process. In order to calibrate all the unknown phase errors introduced in this E-s phase-transfer radio link, this carrier frequency is coherently down-converted and transmitted back to the space VLBI earth station. In this two-way phase calibration, phase errors are mainly introduced by the propagation medium, spacecraft receiver, and space VLBI earth station receiver. These phase errors will contribute to the uncertainty in the determination of the amplitude and relative phase of the non-real-time cross-correlation process, and effectively lower the cross-correlation SNR.

### 5.3.7 Phase noise introduced in propagation

The primary sources of error in determining the on-board frequency are the uplink Doppler shift errors due to spacecraft orbit uncertainty and unmodelled uplink path delay changes in troposphere and in ionosphere. To calibrate these errors, the round-trip phase ( $\phi_r$ ) is measured and used to derive an estimate of the uplink phase

error. The phase ( $\varphi_u$ ) of the on-board reference frequency is retrieved from the round-trip phase ( $\varphi_r$ ) measured on the ground station as follows:

$$\varphi_u = \frac{\varphi_r}{2} \frac{f_u}{f_d} + \pi f_u [\Gamma(f_u) - \Gamma(f_d)], \quad \text{with } \Gamma(f) = 40.3 \Omega / (cf^2) \quad (5.9)$$

where  $f$  ( $=f_u$  or  $f_d$ ) is uplink or downlink propagation frequency (Hz),  $c$  is the velocity of light (m/s),  $\Omega$  is total electron content (electrons/m<sup>2</sup>) of the telemetry link, and  $\Gamma$  is the time delay induced on the propagation frequency due the total electron content of the telemetry link.

If it is assumed that errors are reciprocal, meaning that the uplink and downlink delay errors are the same, and  $f_u \approx f_d$ , then  $\varphi_u \approx \varphi_r/2$ . This approximation gives an accurate value of the uplink phase error assuming that all error sources are non-dispersive and reciprocal. However, since the ionospheric path delay change is dispersive and the transponder turnaround ratio ( $f_u/f_d$ ) is not equal to unity, the full expression is a function of uplink and downlink frequencies and includes another term to account the frequency dependent ionospheric delay. Unless additional information about the total electron content in the ionosphere is provided, a proper correction for the ionospheric delay cannot be made. Nevertheless, this error becomes smaller if frequencies of both  $f_u$  and  $f_d$  are made higher and closer to each other.

Assuming a total electron content of  $8 \times 10^{17}$  electrons/m<sup>2</sup>, the ionospheric time delay errors for the frequency pairs 7.2-8.46 GHz and 15.3-14.2 GHz are calculated to be 286 and 37 picoseconds, respectively. Since the phase transfer error at higher frequencies is much smaller than at lower frequencies, space VLBI systems require higher frequencies in the telemetry links.

### 5.3.8 Phase noise introduced in carrier recovery

At the space VLBI spacecraft receiver and earth station receiver, the carrier recovery process may involve an unmodulated carrier, a BPSK modulated carrier, or a QPSK modulated carrier. For these cases, it has been shown that the phase error variance ( $\sigma^2$ ) for carrier recovery processes is given as follows:

$$\sigma^2 = \begin{cases} (B_L N_0 / P) & \text{for unmodulated carrier} \\ (B_L N_0 / P)(1 + 0.5/\delta) & \text{for BPSK} \\ (B_L N_0 / P)(1 + 2.25/\delta + 1.5/\delta^2 + 0.1875/\delta^3) & \text{for QPSK} \end{cases} \quad (5.10)$$

where  $B_L$  is the bandwidth of the phase lock loop receiver,  $N_0$  is the one-sided noise spectral density,  $P$  is the total carrier power, and  $\delta$  is the symbol SNR. Note that if symbol SNR is high, the variance of the phase errors is approximately same for all the cases. It is easy to see that to reduce the phase noise introduced in carrier recovery, the telemetry link needs to have narrower loop bandwidth, lower system noise density, and higher signal power.

## 5.4 Data rates of existing and planned space VLBI systems

Some existing space VLBI systems typically use data rates of 128 Mbit/s or 144 Mbit/s with QPSK modulation. As such, the maximum required RF bandwidth is in the order of  $4 * R_s = 576$  MHz. However, there are planned space VLBI missions with symbol rates of 1 Gbit/s, which will require greater RF bandwidths. Theoretical studies of propagation effects on wide bandwidth transmissions have indicated that the atmosphere can support several gigahertz of bandwidth at carrier frequencies above 10 GHz. Therefore, transmission bandwidths in the order of 3 GHz to 4 GHz may very well be envisioned in future space VLBI systems.



## CHAPTER 6

### Deep space optical communications

Free-space optical communications systems have been studied and demonstrated in laboratories for many years, but only few of these systems have been deployed aboard spacecraft. Even though most of the technical problems associated with optical communications systems have been solved, advances in microwave sources and high-speed electronics have maintained traditional radio frequency communications systems as the main technology for space-based communications systems. This situation, however, is changing due to the ever-increasing need for high data rate satellite-to-ground, satellite-to-satellite, and deep space optical communications.

#### 6.1 Introduction

Many space agencies and scientific research institutions have made significant investments to advance the telecommunications technologies for optical fibre amplifiers, lasers, and sensitive receivers, which are essential for optical communications systems. Future human expeditions will require a steady stream of high-definition imagery, live video feeds, and real-time data transmission across deep space to enable timely guidance and updates during the long-distance journeys. Currently, with a maximum data rate of 5.2 Mbit/s, the Mars Reconnaissance Orbiter requires 7.5 hours to transmit all of its onboard recorded data, and 1.5 hours to send a single high-resolution image to be processed back on Earth. New missions carrying high-resolution hyperspectral imagers will require much higher data rates for their communications system.

Deep Space Optical Communications (DSOC) is a laser system that will improve the deep-space communications performance by 10 to 100 times over radio frequency technology without increasing mass, volume, or power requirements for spacecraft. DSOC will be capable of providing high bandwidth downlinks from spacecraft in deep space, which will be essential for crewed missions to Mars.

The technical and operational characteristics of optical communications systems for the deep-space missions using 283 THz are given in Recommendation ITU-R SA.1742, and for the space-to-space systems using 354 THz and 366 THz are given in Recommendation ITU-R SA.1805.

#### 6.2 Deep-space optical communications design

The current deep-space optical communications (DSOC) technology employs advanced lasers in the near-infrared region of the electromagnetic spectrum. The key technologies used in the DSOC design include:

- a low-mass spacecraft disturbance isolation and pointing assembly for operating in the presence of spacecraft vibrational disturbance;
- a high-efficiency flight laser transmitter;
- a pair of high-efficiency photon counting detector arrays for the flight optical transceiver and the ground-based receiver (a telescope).

The architecture is based on transmitting a laser beacon from Earth to assist the line-of-sight stabilization of the receiver telescope and to assist pointing the downlink laser beam back to Earth. Also, the architecture depends on efficient codes to reduce the bit error rate of the communications link. The system has the capability to correct for background noise (scattered light) from Earth's atmosphere and the Sun. DSOC system parameters are summarized in Table 6.1.

TABLE 6.1

DSOC system parameters

<b>Spacecraft transceiver</b>	
Laser power	4 W
Laser wavelength	1 550 nm
Telescope aperture	22 cm
Pointing capability	3 degrees off Sun
Mass	29 kg
Power	100 W
<b>Ground transceiver</b>	
Laser power	5 kW
Laser wavelength	1 064 nm
Transmit telescope aperture	1 m
Receive telescope aperture	5.1 m
Receive telescope pointing capability	12 degrees off Sun
Operation	day and night

Since the transmitted beamwidth is inversely proportional to the frequency used, the shorter the wavelength used, the narrower and more focused a beam can be made. The downlink bandwidth (data rate) will depend on the ground telescope diameter and will be less during daytime operations. Given the current hardware, the downlink data rate is expected to reach 100 Mbit/s at a distance of 60 million km and the uplink data rate reaching 292 kbit/s at the same distance.

### 6.3 Link equation

The general method for calculating the received signal power for an optical communications link is similar to that used with traditional radio frequency systems. It is given by equation (6.1).

$$P_s = P_t + G_t + G_r + L_t + L_r + L_p + L_s + L_a \quad (\text{dBW}) \quad (6.1)$$

where:

$P_s$  : received signal power (dBW)

$P_t$  : average laser output power (dBW)

$G_t$  : transmitting telescope gain (dB)

$G_r$  : receiving telescope gain (dBi)

$L_t$  : transmitter losses (dB)

$L_r$  : receiver losses (dB)

$L_p$  : pointing losses (dB)

$L_s$  : free-space loss (dB)

$L_a$  : atmospheric losses (dB).

For deep space optical communication links, the expressions for the transmitting and receiving telescope gains are similar to regular antennas and are given by  $G = \eta \left( \frac{\pi D}{\lambda} \right)^2$ , where  $D$  is the aperture diameter,  $\lambda$  is the wavelength, and  $\eta$  is the efficiency of the aperture. Also, the free-space loss is given by  $L_s = \left( \frac{\lambda}{4\pi R} \right)^2$ , where  $R$  is the range and  $\lambda$  is the wavelength.

The transmitter and receiver losses include the effects of absorption, scattering, and reflection losses in the optical system of the transmitter and receiver, respectively. The pointing losses include the effects of antenna or satellite jitter and mispointing of the transmitting antenna. The atmospheric losses along the space-to-ground link include the effects of atmospheric scatter and turbulence. For space-to-space optical links there would be no atmospheric loss term.

Note that the loss terms in the above equation include variations due to many design parameters, physical effects, and hardware aging. Also, the loss values will depend on the mission requirements and the operational phases of the mission.

## 6.4 Coding

For the future SRS optical communications missions, a fundamentally new channel coding approach is necessary to overcome the fading and phase-corrupting characteristics of a turbulent atmosphere. To meet this challenge, researchers have developed channel interleavers and photon-efficient channel codes for use with direct detection systems. The channel code is called serially-concatenated, convolutionally-coded, pulse position modulation, and it provides a capacity-approaching method. This channel coding has been lately tested on the lunar laser communication demonstration on the Lunar Atmosphere and Dust Environment Explorer (LADEE). The demonstration was successful and proved that data rates up to 622 Mbit/s from lunar orbit using a 0.5 W, 15  $\mu$ rad beam at 1 550 nm are possible.

## 6.5 Psyche mission

A precursor technology demonstration for DSOC was launched in October 2023 on board the Psyche robotic mission to study a large metal asteroid known as Psyche.

The DSOC flight laser transceiver has both a near-infrared laser transmitter to send high-rate data to the ground system, and a sensitive photon-counting camera to receive a ground-transmitted laser. The transceiver is mounted on an isolation-and-pointing assembly that stabilizes the optics and isolates it from spacecraft vibrations.

The DSOC ground system has a high-power near-infrared laser transmitter at Table Mountain observatory in California. It will uplink a low-rate data modulated laser beam to the flight transceiver. The uplink laser will also act as a beacon for the flight transceiver to lock onto. The data sent back by the DSOC transceiver will be collected by the Hale Telescope at Palomar Observatory in California, using a sensitive superconducting nanowire photon-counting receiver to demonstrate high-rate data transfer.

The Psyche spacecraft will reach the asteroid belt between Mars and Jupiter in 2029. The mission is planned to send high-data-rate signals as far out as Mars's greatest distance from Earth. If successful, it will prove the feasibility of higher-data-rate communications capable of sending complex scientific information, high-definition imagery, and video in support of sending humans to Mars.

DSOC first light was achieved in November 2023, and in December the same year the experiment successfully transmitted a 15-second ultra-high-definition video from a location 31 million km away (about 80 times the Earth-Moon distance). The pre-loaded video of a cat named Taters was sent at the system's maximum bit rate of 267 Mbit/s and took 101 seconds to reach Earth.



## CHAPTER 7

### Other aspects of space communications

It is to be noted that this handbook could not cover all the topics related to space research in detail, except only few main topics, to give the reader a quick understanding of space research. The details of most space communications topics are covered in ITU-R Recommendations and Reports. The following paragraphs give brief descriptions of some additional aspects of space communications that are essential to mission operations.

#### 7.1 Emergency mode

Even though the previous chapters do not cover emergency communications, it is very important in mission planning. The spacecraft carries resources and a very detailed safe-mode operations to be carried out during emergencies. During these critical periods or when the communication link margins are low the communication link parameters, including data rates, transmit powers, and antenna gains are adjusted to establish contact. Several ground station antennas could be arrayed to have a very large aperture to receive the downlink signals from spacecraft.

#### 7.2 Beacon mode

In addition to emergency mode operations, missions rely on beacon mode communications during entry-decent-land (EDL) or during approaches to the Sun when normal communications with Earth is hampered by uncertainties or scintillations. During these critical periods, to relay the health of the spacecraft and its telecommunications status, spacecraft uses a simple signal that can be detected with a moderately-sized Earth antenna.

#### 7.3 Small satellites

Lately space research has experienced a very fast development of many short-duration satellites and large constellations of small satellites. These developments have increased many fold the number of operating satellites that require significant amount of spectrum and coordination between space agencies.

#### 7.4 Intra-service interference management

Outside of ITU resources, there are some voluntary external groups, such as Space Frequency Coordination Group (SFCG) and Lunar Mission Spectrum Group (LMSG), that support inter-agency operational coordination to alleviate the intra-service interference issues for planetary and lunar missions. Currently, since the number of missions operating at Mars is increasing, more interferences between the space-to-Earth links from these spacecraft are being experienced.

#### 7.5 Lunar frequency spectrum

Nowadays several space agencies and commercial companies are involved in planning many missions to the Moon for scientific exploration, technology demonstrations, mining and ultimately human settlements on the Moon. In ITU, study groups are working on a lunar frequency spectrum plan to accommodate the needs of all these missions while protecting the Shielded Zone of the Moon for radio astronomy observations.

#### 7.6 Open loop receivers

All the SRS missions make use of closed loop phase lock loop receivers for their telecommunications needs to track and receive signals from spacecraft. But, there are newer receiver methodologies such as open loop spectrum recording or opportunistic multiple spacecraft per aperture. In open loop recording, the receiver does not decode the data being sent by the descending lander but instead record as much of the radio spectrum as possible. Later post process the recorded spectrum to detect the tone of the lander's transmissions within this spectrum.

### **7.7 Single antenna tracking multiple spacecraft**

The multiple spacecraft per aperture (MSPA) is a good example of efficient tracking. MSPA can occur when two or more spacecraft happen to be in the beam of a single Earth station antenna. The downlink data is demodulated simultaneously using different back-end receivers tuned to each individual spacecraft downlink frequency.

### **7.8 Planetary data relay systems**

A data relay system is a network of specialized communications satellites in orbit around Earth that relay signals between satellites, spacecraft, and ground stations on Earth.

Currently there are orbiters around Moon and Mars that serve as data relays between landers and Earth. In the future, the space agencies and commercial companies will deploy more data relay systems around other planets, Moon, Earth, and at Lagrange points. These systems will provide a robust high data rate communications between these assets using radio frequency and optical communication links. The different operational and technical characteristics of these systems need to be studied.

## 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 of the space research service
- 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 space research service (deep space)
- SA.1018 Hypothetical reference system for networks/systems comprising data relay satellites in the geostationary orbit and their user spacecraft in low Earth orbits
- SA.1019 Frequency bands and transmission directions for data relay satellite networks/systems
- SA.1154 Provisions to protect the space research (SR), space operations (SO) and Earth-exploration satellite services (EESS) and to facilitate sharing with the mobile service in the 2 025-2 110 MHz and 2 200-2 290 MHz bands
- SA.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.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
- 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
- SA.2078 Protection of SRS earth stations from mobile (aircraft) stations in the 2 200-2 290 MHz band
- SA.2079 Frequency sharing between space research service and fixed satellite service (space-to-Earth) systems in the 37.5-38 GHz band
- SA.2141 Characteristics of space research service systems in the frequency range 14.8-15.35 GHz
- SA.2142 Methodologies for calculating coordination areas around Earth exploration satellite and space research earth stations to avoid harmful interference from IMT-2020 systems in the frequency bands 25.5-27 GHz and 37-38 GHz
- SA.2155 Guidelines on the use of the frequency band 2 200-2 290 MHz by Earth exploration-satellite service/space research service/space operation service satellite networks or systems that are not using spread-spectrum modulation
- SA.2156 Guidelines on the use of the frequency band 2 025-2 110 MHz by Earth exploration-satellite service/space research service/space operation service satellite networks or systems that are not using spread-spectrum modulation
- 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
- RS.1628 Feasibility of sharing in the band 35.5-36 GHz between the Earth exploration-satellite service (active) and space research service (active), and other services allocated in this band
- RS.1749 Mitigation technique to facilitate the use of the 1 215-1 300 MHz band by the Earth exploration-satellite service (active) and the space research service (active)
- RS.2064 Typical technical and operating characteristics and frequency bands used by space research service (passive) observation systems
- RS.2065 Protection of space research service (SRS) space-to-Earth links in the 8 400-8 450 MHz and 8 450-8 500 MHz bands from unwanted emissions of synthetic aperture radars operating in the Earth exploration-satellite service (active) around 9 600 MHz
- F.1248 Limiting interference to satellites in the space science services from the emissions of trans-horizon radio-relay systems in the bands 2 025-2 110 MHz and 2 200-2 290 MHz
- F.1249 Technical and operational requirements that facilitate sharing between point-to-point systems in the fixed service and the inter-satellite service in the band 25.25-27.5 GHz
- SM.1539 Variation of the boundary between the out-of-band and spurious domains required for the application of Recommendations ITU-R SM.1541 and ITU-R SM.329
- SM.1541 Unwanted emissions in the out-of-band domain

**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
- SA.2271 Sharing conditions between space research service proximity operations links and fixed and mobile service links in the 410-420 MHz band
- SA.2276 Protection of SRS earth stations from transmitting aircraft stations in the 2 200-2 290 MHz band
- SA.2277 Sharing studies between mobile-satellite service and space research service in the 22-26 GHz range
- SA.2307 Protection of SRS and FSS systems sharing the 37.5-38 GHz band
- SA.2309 Compatibility between EESS (Earth-to-space) and the space research service or the space operation service in the band 7 100-7 235 MHz
- SA.2312 Characteristics, definitions and spectrum requirements of nanosatellites and picosatellites, as well as systems composed of such satellites
- SA.2325 Sharing between space-to-space links in space research, space operation and Earth exploration-satellite services and IMT systems in the frequency bands 2 025-2 110 MHz and 2 200-2 290 MHz
- SA.2348 Current practice and procedures for notifying space networks currently applicable to nanosatellites and picosatellites
- SA.2349 Compatibility between GSO EESS (Earth-to-space), and the fixed service, the mobile service, the space research service, or the space operation service in the band 7 190-7 235 MHz
- SA.2401 Modelling methods to predict the gain and radiation patterns of large antennas
- SA.2553 Technical and operational characteristics for space research systems in the vicinity of the Moon



## ATTACHMENT 2

## SRS frequency bands and related pfd limits

TABLE A2.1

## Frequency bands allocated for space research use

Frequency		Use	Frequency		Use
2 501-2 502	kHz	srs	8 550-8 650	MHz	SRS (active)
5 003-5 005	kHz	srs	9 300-9 800	MHz	SRS (active)
10 003-10 005	kHz	srs	9 800-9 900	MHz	srs (active)
15 005-15 010	kHz	srs	10.6-10.7	GHz	SRS (passive)
18 052-18 068	kHz	srs	12.75-13.25	GHz	srs (s-E, ds)
19 990-19 995	kHz	srs	13.25-13.4	GHz	SRS (active)
25 005-25 010	kHz	srs	13.4-13.75	GHz	SRS
30.005-30.01	MHz	SRS	13.75-14.3	GHz	srs
39.986-40.02	MHz	srs	14.4-14.47	GHz	srs (s-E)
40.98-41.015	MHz	srs	14.5-14.8	GHz	srs
			14.8-15.35	GHz	SRS
137-138	MHz	SRS (s-E)	15.20-15.35	GHz	SRS (passive)
138-143.6	MHz	srs (s-E)	15.35-15.4	GHz	SRS (passive)
143.6-143.65	MHz	SRS (s-E)	16.6-17.1	GHz	SRS (E-s, ds)
143.65-144	MHz	srs (s-E)	17.2-17.3	GHz	SRS (active)
400.15-401	MHz	SRS (s-E)	18.6-18.8	GHz	srs/SRS/srs (passive)
410-420	MHz	SRS (s-s)	21.2-21.4	GHz	SRS (passive)
1 215-1 300	MHz	SRS (active)	22.21-22.5	GHz	SRS (passive)
1 370-1 400	MHz	SRS (passive)	22.55-23.15	GHz	SRS (E-s)
1 400-1 427	MHz	SRS (passive)	23.6-24	GHz	SRS (passive)
1 660.5-1 668.4	MHz	SRS (passive)	25.5-27	GHz	SRS (s-E)
2 025-2 110	MHz	SRS (E-s, s-s)	31-31.3	GHz	srs
2 110-2 120	MHz	SRS (E-s, ds)	31.3-31.8	GHz	SRS (passive)
2 200-2 290	MHz	SRS (s-E, s-s)	31.8-32.3	GHz	SRS (s-E, ds)
2 290-2 300	MHz	SRS (s-E, ds)	34.2-34.7	GHz	SRS (E-s, ds)
2 640-2 690	MHz	srs (passive)	34.7-35.2	GHz	srs
2 690-2 700	MHz	SRS (passive)	35.5-36	GHz	SRS (active)
3 100-3 300	MHz	srs (active)	36-37	GHz	SRS (passive)
4 950-5 000	MHz	srs (passive)	37-38	GHz	SRS (s-E)
5 250-5 255	MHz	SRS	40-40.5	GHz	SRS (E-s)
5 255-5 570	MHz	SRS (active)	50.2-50.4	GHz	SRS (passive)
5 670-5 725	MHz	srs (ds)	52.6-59.3	GHz	SRS (passive)
7 145-7 190	MHz	SRS (E-s, ds)	65-66	GHz	SRS
7 190-7 235	MHz	SRS (E-s)	74-84	GHz	srs (s-E)
8 400-8 450	MHz	SRS (s-E, ds)	86-92	GHz	SRS (passive)
8 450-8 500	MHz	SRS (s-E)	94-94.1	GHz	SRS (active)
100-102	GHz	SRS (passive)	200-209	GHz	SRS (passive)
105-122.25	GHz	SRS (passive)	217-231.5	GHz	SRS (passive)
148.5-151.5	GHz	SRS (passive)	235-238	GHz	SRS (passive)
164-167	GHz	SRS (passive)	250-252	GHz	SRS (passive)
174.8-191.8	GHz	SRS (passive)			

TABLE A2.2

## pfd limits for the transmit frequency bands used by SRS

Frequency	Use	pfd limit for angles of arrival ( $\theta$ ) above the horizontal plane (dBW/m <sup>2</sup> )			Reference bandwidth
		$0^\circ \leq \theta \leq 5^\circ$	$5^\circ < \theta \leq 25^\circ$	$25^\circ < \theta \leq 90^\circ$	
410-420 <sup>(1)</sup>	MHz SRS(s-s)	-153	$-153 + 0.077(\theta - 5)$	-148	4 kHz
2 025-2 110	MHz SRS (E-s, s-s)	-154	$-154 + 0.5 (\theta - 5)$	-144	4 kHz
2 200-2 290	MHz SRS (s-E, s-s)	-154	$-154 + 0.5 (\theta - 5)$	-144	4 kHz
2 290-2 300	MHz SRS (s-E, ds)	-154	$-154 + 0.5 (\theta - 5)$	-144	4 kHz
5 670-5 725	MHz srs (ds)	-152	$-152 + 0.5 (\theta - 5)$	-142	4 kHz
8 400-8 450	MHz SRS (s-E, ds)	-150	$-150 + 0.5 (\theta - 5)$	-140	4 kHz
8 450-8 500	MHz SRS (s-E)	-150	$-150 + 0.5 (\theta - 5)$	-140	4 kHz
14.8-15.35	GHz SRS (s-E, s-s)	See Resolution <b>678 (WRC-23)</b>			1 MHz
22.55-23.55	GHz ISS (s-s)	-115	$-115 + 0.5 (\theta - 5)$	-105	1 MHz
25.25-27.5	GHz ISS (s-s)	-115	$-115 + 0.5 (\theta - 5)$	-105	1 MHz
25.5-27	GHz SRS (s-E)	-115	$-115 + 0.5 (\theta - 5)$	-105	1 MHz
31-31.3	GHz srs	-115	$-115 + 0.5 (\theta - 5)$	-105	1 MHz
31.8-32.3	GHz SRS (s-E, ds)	-120	$-120 + 0.75 (\theta - 5)$	-105	1 MHz
34.7-35.2	GHz srs	-115	$-115 + 0.5 (\theta - 5)$	-105	1 MHz
35.5-36 <sup>(2)</sup>	GHz SRS (active)		$\leq -73.3 \text{ dBW/m}^2$		0.5 GHz
37-38	GHz SRS (s-E, NGSO)	-120	$-120 + 0.75 (\theta - 5)$	-105	1 MHz
37-38 <sup>(3)</sup>	GHz SRS (s-E, NGSO, ds)	-115	$-115 + 0.5 (\theta - 5)$	-105	1 MHz
37-38	GHz SRS (s-E, GSO)	-125	$-125 + (\theta - 5)$	-105	1 MHz

<sup>(1)</sup> By RR No. **5.268**, this pfd limit applies for arrival angles between 0-5 degrees, 5-70 degrees, and 70-90 degrees.

<sup>(2)</sup> By RR No. **5.549A**, this pfd limit applies for any angle greater than 0.8 degree from the transmit beam centre.

<sup>(3)</sup> By RR No. **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.

Legend:

SRS/srs = Non-specific  
s-E = space-to-Earth  
E-s = Earth-to-space  
s-s = space-to-space  
ds = deep-space

## ATTACHMENT 3

### Space exploration missions

There are many agencies and organisations around the World with interest in space exploration. These agencies have already launched many space missions and planning to launch more missions to explore our solar system and beyond. Some examples of past, currently in operation and planned in the future space missions and their objectives are given below. From planning a mission to building, launching, and operating spacecraft, missions like these take years to accomplish and require international cooperation for them to be successful. Space exploration missions make great discoveries and bring invaluable data for humans to understand the universe around us.

#### Universe Research and Exploration

ARIEL	ESA (European Space Agency)'s Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL) will inspect the atmospheres of a thousand exoplanets in our galaxy, reveal their atmospheric compositions and the presence of clouds and weather conditions. Ariel is planned to be launched in 2029.
CHEOPS	ESA's CHaracterising ExO Planet Satellite is the first mission dedicated to studying bright, nearby stars that are already known to host exoplanets, in order to make high-precision observations of the planet's size as it passes in front of its host star. It was launched in 2019.
DAMPE	China's the Dark Matter Particle Explorer, launched in December 2015 to find and study dark matter particle through high-resolution observation of high electron, gamma-ray spectrum and its space distribution. It studies the origin of cosmic ray through observation of high energy electron spectrum and anisotropy above TeV, and also studies the propagation and acceleration mechanism of cosmic ray through the observation of its heavy ion spectra.
EP	China's Einstein-Probe launched in 2024. It is used to explore time-domain census of soft X-ray transient and variable sources in the universe, as well as systematic census of soft X-ray transients and variability of known X-ray sources over wide time-scales at high cadence. Discover quiescent black holes over all astrophysical mass range and other compact objects via high energy transients. Also discover and locate electromagnetic-wave sources of gravitational-wave events by synergy with new gravitational-wave detectors.
EUCLID	ESA's EUCLID mission was launched in 2023 and is designed to explore the composition and evolution of the dark Universe, mapping the large-scale structure of the Universe.
GAIA	ESA's GAIA is creating a precise three-dimensional map of stars throughout our Milky Way galaxy and beyond, mapping their motions, luminosity, temperature and composition. GAIA was launched in 2013.

GECAM	China's Gravitational wave high-energy Electromagnetic Counterpart All-sky Monitor, launched in December 2020. It will conduct all-day monitoring of high-energy celestial burst phenomena such as gravitational wave gamma bursts, rapid radio bursts, special gamma bursts and magnetostar bursts, and promote the solution of the formation and evolution of dense celestial bodies such as black holes and neutron stars, as well as the mystery of the merger of two compact stars. In addition, the GECAM satellite will also detect high-energy radiation phenomena such as solar flares, Earth gamma flashes, and Earth electron beams in space, providing scientific observation data for further research on their physical mechanisms.
Hubble	NASA (National Aeronautics and Space Administration (United States of America))'s Hubble Space Telescope is a multipurpose astrophysics and planetary science observatory. It was launched into low Earth orbit in 1990 and remains in operation. It was not the first space telescope, but it is one of the largest and most versatile, renowned both as a vital research tool and as a public relations boon for astronomy.
HXMT	China's Hard X-ray Modulation Telescope, launched in June 2017. It is used for large-scale X-ray measurement, including cosmic and galactic diffuse X-ray background and discover new transients and monitor bright sources. Broad band (1~250keV) and large collection area (5000 cm <sup>2</sup> @100keV) pointed observations of high energy objects, and dynamics and radiation near black hole horizons of stellar mass are also its function.
INTEGRAL	ESA's International Gamma-Ray Astrophysics Laboratory (INTEGRAL) objective is to track violent events across the Universe, observing celestial objects simultaneously in gamma rays, X-rays and in visible light. INTEGRAL launched in 2002.
JWST	NASA's James Webb Space Telescope launched in 2021 to build on the Hubble Space Telescope's capabilities.
PLATO	ESA's "PLANetary Transits and Oscillations of stars" (PLATO) will study terrestrial exoplanets in orbits up to the habitable zone of Sun-like stars, measuring their sizes and discover exomoons and rings around them. The launch is planned for 2026.
RST	NASA's Nancy Grace Roman Space Telescope will launch in 2027. It is designed to unravel the secrets of dark energy and dark matter, search for and image exoplanets, and explore many topics in infrared astrophysics.
ShiJian-10	China's ShiJian-10, launched in April 2016 to explore the basic laws of motion for matter, high performance material preparation, mechanism of combustion, biological effects of gravity or space radiation, and space biotechnology.
TESS	NASA's Transiting Exoplanet Sensing Satellite hunts for exoplanets around a specific type of bright stars.
Voyager-2	NASA's Voyager 2 is the only spacecraft to have visited Uranus and Neptune. It flew past Uranus in 1986 and Neptune in 1989. It is now exploring interstellar space.
XMM	ESA's X-ray Multi-Mirror Mission (XMM) studies X-ray sources across the Universe: galactic centres, stars at all stages of their life, black holes, and following-up on explosive events like gamma-ray bursts. XMM was already launched in 1999 and is still operational today.
XPOSAT	India's X-ray Polarimeter satellite (XPOSAT) aims to study bright astronomical X-ray sources like black holes and neutron stars by measuring the polarization of their emissions and provide spectroscopic information. XPOSAT was launched in 2024 and is currently operational.

XRISM JAXA (Japan Aerospace Exploration Agency (Japan))’s X-ray Imaging and Spectroscopy Mission (XRISM) is a new X-ray astronomy satellite that observes stars, galaxies, and the ethereal “plasma” weaving through them. XRISM launched in 2023 and is unveiling the universe’s secrets with a brand-new high-precision X-ray imaging spectroscopy technology.

### Geospace Research

ARASE JAXA’s Exploration of energization and Radiation in Geospace “ARASE” (ERG) launched in 2016 to observe plasma particles and field/waves inside the Van Allen radiation belts where the highest energy particles are trapped in geospace in order to reveal how space storms develop.

CASEarth China’s CASEarth by Chinese Academy of Sciences (CAS) launched in 2021 to establish an international big earth data science center, which will have three main objectives: a) building the Most Advanced Big Earth Data Infrastructure; b) developing innovative big earth data platforms to promote discipline development, and c) building a decision support system.

### Lunar Exploration

Chandrayaan-1 India’s planetary exploration program began with successful launch of Chandrayaan-1 in 2008 with lunar orbiter which made significant finding including discovery of water signature on lunar surface.

Chandrayaan-2 India’s Chandrayaan-2 is composed of an orbiter, lander and rover to explore the unexplored South Pole of the Moon. The mission studies the topography, seismography, mineral identification and distribution, surface chemical composition, thermo-physical characteristics of top soil and composition of the tenuous lunar atmosphere.

Chandrayaan-3 India’s mission was successfully launched on 14 July 2023 and the lander Vikram successfully soft landed in the lunar near South Pole region on 23 August 2023, achieving humanity’s first soft landing near south pole.

Chandrayaan-4 India’s fourth mission to the Moon is envisaged as a lunar sample return mission. The prime objective of the mission is to bring the lunar samples from southern high latitudes of the Moon, safely to Earth for conducting transformative scientific analysis.

Chang’e-4 China’s Chang’e-4 (Moon Goddess) mission performed the first soft landing on the far side of the Moon in 2018, where it studies an ancient region.

Chang’e-5 China’s Chang’e-5 returned lunar samples to Earth in 2020, and is on an extended mission to study the Sun and possibly asteroids.

KAGUYA (SELENE) JAXA’s KAGUYA (SELENE) launched in 2007 to obtain scientific data of the lunar origin and evolution and to develop the technology for the future lunar exploration.

KPLO The Korea Pathfinder Lunar Orbiter is a technology demonstration mission planned for 2022.

LRO NASA’s Lunar Reconnaissance Orbiter is a robotic mission that set out to map the moon’s surface. LRO observations have enabled numerous groundbreaking discoveries, creating a new picture of the moon as a dynamic and complex body.

LUPEX/Chandrayaan-5 Lunar Polar Exploration (LUPEX) is a joint JAXA and ISRO (Indian Space Research Organisation (India)) mission to the lunar South Pole to measure the quantity and quality of water on the lunar surface and sub-surface, explore other resources, determine the regolith composition and gaining expertise in exploring the surface of the Moon.

SLIM JAXA's Smart Lander for Investigating Moon (SLIM) launched in 2023, and achieved a small scale, light weight probe system and pinpoint landing technology, in addition to contributing to future lunar probes. The small robots, LEV1 & LEV2, released by SLIM successfully operated on the lunar surface.

VIPER NASA's the Volatiles Investigation Polar Exploration Rover launches to the Moon's south pole in 2024 to explore the extreme environment of the Moon in search of ice and other potential resources.

### **Mars Exploration**

Curiosity NASA's Curiosity rover explores an ancient lake bed on Mars that once had conditions that could have supported life.

EMM The Emirates Mars Mission, known also as Al-Amal (Hope), is the first planetary mission by an Arab country (UAE), which arrived at Mars in February 2021. The space probe will study daily and seasonal weather cycles, weather events in the lower atmosphere such as dust storms, and how the weather varies in different regions of the planet.

ERO ESA's Earth Return Orbiter (ERO) will be part of the Mars Sample Return Campaign. ERO is dedicated to capture a sample capsule orbiting around Mars and return to Earth. The launch is planned for no earlier than 2027 with an arrival to Mars in 2029.

ExoMars ESA's ExoMars Programme consists of two components, the Trace Gas Orbiter (TGO), launched in 2016, and the Rosalind Franklin Rover (RFM), which is planned to be launched not before 2028. The TGO searches Mars for atmospheric gases linked to life as we know it. The RFM will be Europe's first rover on Mars and will collect and analyse ground samples for biomarkers from the early history of the planet.

InSight NASA's Interior Exploration using Seismic Investigations, Geodesy, and Heat Transfer is a lander on Mars to study the planet's interior.

Mangalyaan India's Mangalyaan orbiter is a technology demonstration mission studying the planet Mars.

MAVEN NASA's Mars Atmosphere and Volatile Evolution orbiter studies what happened to Mars' atmosphere. It is exploring the planet's upper atmosphere, ionosphere and interactions with the sun and solar wind.

MEX Launched in 2003, ESA's Mars Express mission surveys the planet Mars, maps the chemical composition of its atmosphere, searches for subsurface water and studies Mars' innermost moon Phobos.

MMX JAXA's Martian Moons eXploration (MMX) mission is to travel to Mars and survey the red planet's two moons: Phobos and Deimos. MMX launches in 2026 to explore both moons and to collect samples from Phobos for bringing them back to the Earth by 2031.

MRO NASA's Mars Reconnaissance Orbiter studies the planet's atmosphere and terrain from orbit with a high-powered camera and also serves as a key data relay station for other Mars missions, including the Mars rovers.

MSR Mars Sample Return is a series of missions by NASA and ESA to return samples from Mars to Earth in the early 2030s.

Odyssey NASA's long-lived Odyssey mission monitors surface changes of planet Mars. It holds the record for the longest continually active spacecraft in orbit around a planet other than Earth. It has been in orbit since 2001.

Perseverance	NASA's Perseverance rover landed onto Mars in February 2021 and will search for past habitability of Mars and collect samples for return to Earth. The Mars Helicopter (Ingenuity), which travelled to Mars with Perseverance, achieved a historic moment by testing the first powered flight on Mars.
Tianwen-1	China's Tianwen-1 is an orbiter and rover mission that arrived to Mars in February 2021 to investigate Martian surface geology and internal structure, to search for indications of current and past presence of water, and to characterize the space environment and the atmosphere of Mars.
Tianwen-3	China's Tianwen-3 is a Mars sample return mission, scheduled for launch around 2028. The Tianwen-3 is composed of a lander, an ascender, a server, an orbiter and a returner. Its scientific objectives are to study the potential traces of life on Mars, geological structure and atmospheric characteristics.

### **Asteroids Exploration**

DART	NASA's Double Asteroid Redirection Test spacecraft launched in 2021 and will crash into a small asteroid in October 2022, validating technology useful for deflecting any potentially hazardous asteroids that could threaten Earth.
DESTINY+	JAXA's DESTINY+ launches in 2028 to explore the asteroids: (99942) Apophis and (3200) Phaethon performing high-speed flyby observations for the acquisition of navigational control technologies to visit multiple small body targets by one spacecraft.
Hayabusa	JAXA's Hayabusa launched in 2003 for experimental research on new engineering technologies necessary for returning planetary samples (sample return) to the Earth including electrical propulsion, autonomous navigation, sampler and reentry capsule. Hayabusa made two landings to collect samples from the asteroid (25143) Itokawa approximately 300 million km away from the Earth in 2005, and successfully brought the capsule with the samples back to the Earth in 2010.
Hayabusa2	JAXA's Hayabusa2, which is the second asteroid sample return mission, launched in 2014 to head for the asteroid 1999 JU3, (162173) Ryugu, and arrived at the asteroid in 2018. The asteroid samples contained in its capsule and its Earth re-entry was in 2020. Once separated the capsule, Hayabusa2 turned its face towards new asteroid 1998 KY26 through the asteroid 2001 CC21, (98943) Torifune.
Hera	ESA's Hera spacecraft launched in 2024 to investigate the binary asteroid, including the very first assessment of its internal properties, and to measure in great detail the outcome of NASA's DART mission kinetic impactor test.
Lucy	NASA's Lucy mission launched in 2021 to explore asteroids that share Jupiter's orbit.
NEA Scout	NASA's Near-Earth Asteroid Scout is a miniaturized spacecraft, known as a CubeSat. It launches in 2023 to demonstrate a low-cost method of asteroid reconnaissance.
OSIRIS-REx	NASA's OSIRIS-REx collected a sample of asteroid Bennu for return to Earth in 2023.
Psyche	NASA's Psyche launches in August 2022. It is a journey to a unique metal-rich asteroid, called Psyche, orbiting the Sun between Mars and Jupiter. The asteroid is unique as it appears to be the exposed nickel-iron core of an early planet, one of the building blocks of our solar system.

**RAMSES** ESA's Rapid Apophis Mission for Space Safety (RAMSES) is a follow-up mission to HERA to characterize and monitor the dynamic behaviour of the asteroid 99942 Apophis prior to, during and after its close encounter with Earth in 2029. The launch of RAMSES is planned for 2028.

**Tianwen-2** China's Tianwen-2 small-body exploration mission launched in May 2025. It is designed to execute a dual-objective exploration in a single flight: conducting rendezvous and proximity observation of the near-Earth asteroid 2016 HO3 followed by sample return, and performing rendezvous exploration of main-belt comet 311P.

### **Solar System Exploration**

**Aditya-L1** The first Indian space mission to study the Sun. The payloads cover the Sun's photosphere (ultraviolet (UV) and soft and hard X-rays), chromosphere (UV) and corona (visible and NIR). This satellite was launched on 2 September 2023 and Halo-Orbit Insertion (HOI) was accomplished on 6 January 2024.

**ASO-S** China's Solar Observatory (ASO-S), launched in October 2022. It can simultaneously observe the full disc vector magnetic field, non-thermal images of hard-rays, and initiation of coronal mass ejections (CME). It is used to understand the causality between magnetic field and flares, magnetic field and CMEs, flares and CMEs.

**BepiColombo** ESA and JAXA's BepiColombo is an international plan to explore Mercury jointly by employing two orbiters: Mercury Planetary Orbiter (MPO) and Mercury Magnetospheric Orbiter (MMO) named "MIO". They launched in 2018 and arrive at Mercury in 2026.

**COMET-I** ESA's Comet Interceptor, or COMET-I, is planned to visit a long period comet coming from the outer Solar System, to study the evolutionary path of comets and the dawn of our Solar System. Comet-I will be launched in 2029.

**DAVINCI** NASA's Deep Atmosphere Venus Investigation of Noble gases, Chemistry and Imaging mission, launching between 2028 and 2030, will be the first to study Venus through both flybys and descent. The spacecraft is expected to explore the layered Venusian atmosphere and reach its surface by June 2031.

**Dragonfly** NASA's Dragonfly mission launches in 2027 to explore Saturn's moon Titan. It will send a robotic rotorcraft to the surface of Titan. It would be the first powered and fully controlled atmospheric flight on any moon, to study the prebiotic chemistry and extraterrestrial habitability. It will then use its vertical take offs and landings capability to move between exploration sites.

**EnVision** ESA's EnVision is an orbital mission to Venus, which will launch no earlier than 2031, to perform high-resolution radar mapping and atmospheric studies of Venus.

**Europa Clipper** NASA's Europa Clipper launches in 2024 to determine whether Jupiter's moon Europa could support life.

**HINODE** JAXA's HINODE (SOLAR-B) is an observatory satellite to study the magnetic field of the Sun's photosphere in an unprecedented detail together with the dynamics of the corona, which then helps us to understand the impact of the Sun on the Earth. Launched in 2006, HINODE continues to provide unique and valuable data.

**JUICE** ESA's JUpiter's ICy moons Explorer launched in 2023 to explore Jupiter and its icy moons Europa, Callisto, and Ganymede.

Juno	NASA's Juno spacecraft embarked on a 5-year journey to our solar system's largest planet—the gas giant Jupiter. Its mission was to probe beneath the planet's dense clouds and answer questions about the origin and evolution of Jupiter, our solar system, and giant planets in general across the cosmos.
NEO Surveyor	NASA's Near-Earth Object Surveyor is designed to help advance the planetary defense efforts to discover and characterize most of the potentially hazardous asteroids and comets that come within 30 million miles of Earth's orbit.
NEOWISE	NASA repurposed Wide-field Infrared Survey Explorer (WISE) mission in 2013 to hunt for dangerous asteroids. NEOWISE harvests measurements of asteroids and comets from the WISE images and provides a rich data archive to search for solar system objects.
New Horizons	New Horizons is a NASA mission to study the dwarf planet Pluto, its moons, and other objects in the Kuiper Belt.
SMILE-S	China's CAS-ESA Joint Scientific Space Mission-Solar wind Magnetosphere Ionosphere Link Explorer is planned to launch in 2026. It can study the interaction between Earth magnetosphere and solar wind. Provide more detailed information that could help scientists understand how the sun's effect on Earth's magnetic field influences events on the planet.
Solar Orbiter	ESA's Solar Orbiter, launched in 2020, is designed to especially study the polar regions of the Sun, to measure the composition of the solar wind and to trace its origin to the corresponding area on the Sun's surface.
SOLAR-C	JAXA's SOLAR-C is a solar observation satellite scheduled for launch in 2028. It will carry an EUV High-throughput Spectroscopic Telescope (EUVST) with a spectral irradiance monitor (SoSpIM) to conduct high-spatial-resolution and high-throughput spectroscopic observations of UV radiations from the Sun, with the aim of unravelling the mysteries of the solar atmosphere.
VERITAS	NASA's Venus Emissivity, Radio Science, InSAR, Topography And Spectrometry mission, also launching between 2028 and 2030, is a Venus orbiter designed to reveal how the paths of Venus and Earth diverged, and how Venus lost its potential as a habitable world.

### **Human Exploration in Space**

Artemis	NASA's Artemis program will return humans to the Moon. The first test flight, Artemis 1, launched in 2022. NASA plans to land the first woman and first person of color on the Moon, using innovative technologies to explore more of the lunar surface than ever before.
Gaganyaan	India's Gaganyaan mission will be the country's maiden human spaceflight endeavour to send humans to space.
ISS	The International Space Station studies the health effects of long-term spaceflight and prepares astronauts for deep space missions.
Tianhe	The Tianhe core module, launched to Earth orbit in 2021, is the first module of China's space station, supporting spacecraft rendezvous, docking and berthing.

### **Space Technology Research**

ACS3	NASA's Advanced Composite Solar Sail System mission, launched to Earth orbit in 2024, is a solar sail mission that will test out new sail boom materials.
DRO	China's DRO mission, launched in 2024, is designed to verify long-distance measurement and communication technologies in the Cislunar space.

- IKAROS JAXA's IKAROS is a small scale demonstration satellite that uses solar power generated via thin film solar cells attached to its sail, called a solar sail. IKAROS launched in 2010, and the experiment verified that the satellite could be accelerated with solar power while it was also possible to control the trajectory of the satellite with LCD devices, etc. and verified navigational technology that made use of the solar sail, that were all remarkable firsts in the world.
- LightSail 2 The Planetary Society's LightSail 2 spacecraft, launched in 2019, uses sunlight alone to change its orbit, and is currently testing advance solar sailing technology.
- QUESS China's Quantum Experiments at Space Scale, launched in August 2016. It achieves a significant breakthrough in space-based practical quantum communication by implementing a remote quantum communication network based on high-speed quantum key distribution (QKD) between satellites and ground stations. It is based on quantum entanglement distribution and quantum teleportation on a spatial scale, and conducts basic testing of quantum mechanical laws on a global scale.
- Solar Cruiser NASA's Solar Cruiser launches in 2025 to test a large solar sail at an artificial orbit between the Earth and Sun.
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