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Telecommunication requirements for manned and unmanned deep-space research

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RECOMMENDATION ITU-R SA.1014-2

Telecommunication requirements for manned and unmanned deep-space research

(1994-2006-2011)

Scope

This Recommendation briefly describes some essential characteristics of deep-space telecommunications. These characteristics influence or determine the requirements for selection of candidate bands, coordination, band sharing and protection from interference.

The ITU Radiocommunication Assembly,

considering

a) that telecommunications between the Earth and stations in deep space have unique requirements;

b) that these requirements affect the selection of candidate band, band sharing, coordination, protection from interference and other regulatory and frequency management matters,

recommends

1 that the requirements and characteristics described in Annex 1 for deep-space telecommunications should be taken into account concerning deep-space research and its interaction with other services.

Annex 1

Telecommunication requirements for manned and unmanned deep-space research

1 Introduction

This Annex presents some characteristics of deep-space research missions, the functional and performance requirements for telecommunications needed to conduct deep-space research by means of spacecraft, and the technical methods and parameters of systems used in connection with such missions.

Considerations regarding bandwidth characteristics and requirements are found in Report ITU-R SA.2177.

2 Telecommunication requirements

Deep-space missions require highly reliable radiocommunications over long periods of time and great distances. For example, a spacecraft mission to gather scientific information at the planet Neptune takes eight years and requires telecommunication over a distance of 4.65×10^9 km. The need for high e.i.r.p. and very sensitive receivers at earth stations is a result of the large radiocommunication distances involved in deep-space research.

Continuous usage of deep-space radiocommunication bands is a consequence of the several missions now in existence and others being planned. Because many deep-space missions continue for periods of several years, and because there are usually several missions in progress at the same time, there is a corresponding need for radiocommunication with several spacecraft at any given time.

In addition, each mission may include more than one spacecraft, so that simultaneous radiocommunication with several space stations will be necessary. Simultaneous coordinated radiocommunication between a space station and more than one earth station may also be required.

2.1 Telemetering requirements

Telemetering is used to transmit both maintenance and scientific information from deep space.

Maintenance telemetering information about the condition of the spacecraft must be received whenever needed to ensure the safety of the spacecraft and success of the mission. This requires a weather independent telecommunications link of sufficient capacity. This requirement is a partial determinant of the frequency bands that are preferred for deep-space research (see Report ITU-R SA.2177).

Science telemetering involves the sending of data that is collected by the on-board scientific instruments. The required data rate and acceptable error rate may be quite different as a function of the particular instrument and measurement. Table 1 includes typical ranges of data transmission rates for scientific and maintenance telemetering.

TABLE 1

Required bit rates for deep-space research

Direction and function	Link characteristic		
	Weather independent	**Normal**	**High data rate**
Earth-to-space			
Telecommand (bit/s)	1-1 000	1-1 000	1-2 000
Computer programming (kbit/s)	1-50	1-100	1-200
Voice (kbit/s)	45	45	45
Television (Mbit/s)	1-4	0.2-12	6-100
Ranging (Mbit/s)	1	10	100
Space-to-Earth			
Maintenance telemetering (bit/s)	8-500	8-500	$8\text{-}2 \times 10^5$
Scientific data (kbit/s)	0.008-115	1-500	$40\text{-}3 \times 10^5$
Voice (kbit/s)	45	45	45
Television (Mbit/s)	0.2-0.8	0.2-8	6-1 000
Ranging (Mbit/s)	1	10	100

Telemetering link capacity has steadily increased with the development of new equipment and techniques. This increase can be used in two ways:

– to gather larger amounts of scientific data at a given planet or distance; and

– to permit useful missions to more distant planets.

For a particular telemetering system, the maximum possible data rate is proportional to the inverse square of the radiocommunication distance. The same link capacity that provides for a data rate of 134 kbit/s from the vicinity of the planet Jupiter (9.3×10^8 km) would also provide for a data rate of 1.74 Mbit/s from the vicinity of the planet Venus (2.58×10^8 km). Because higher data rates require wider transmission bandwidths, the ability to effectively utilize the maximum telemetering capability depends on the width of allocated bands, and the number of simultaneous mission spacecraft that are within the earth station beamwidth and are operating in the same band.

An important contribution to telemetering has been the development of coding methods that permit operation with a lower signal-to-noise ratio. The coded signal requires a wider transmission bandwidth. The use of coded telemetering at very high data rates may be limited by allocation width.

2.2 Telecommand requirements

Reliability is the principal requirement of a telecommand link. Commands must be received accurately and when needed. The telecommand link is typically required to have a bit error rate not greater than 1×10^{-6}. Commands must be received successfully, without regard to spacecraft orientation, even when the primary high gain antenna may not be pointed to Earth. For such circumstances, reception using a nearly omnidirectional spacecraft antenna is required. Very high e.i.r.p. is needed at earth stations because of low spacecraft antenna gain, and to provide high reliability.

With computers on the spacecraft, automatic sequencing and operation of spacecraft systems is largely predetermined and stored on-board for later execution. For some complicated sequences, automatic operation is a requirement. Telecommand capability is required for in-flight alteration of stored instructions, which may be needed to correct for observed variations or malfunctions of spacecraft behaviour. This is particularly true for missions of long duration, and for those circumstances where sequencing is dependent on the results of earlier spacecraft events. For example, the commands for spacecraft trajectory correction are based on tracking measurements and cannot be predetermined.

The range of required command data rates is given in Table 1.

Reliable telecommand includes the need for reliable maintenance telemetering that is used to verify that commands are correctly received and loaded into command memory.

2.3 Tracking requirements

Tracking provides information used for spacecraft navigation and for radio science studies.

2.3.1 Navigation

The tracking measurements for navigation include radio-frequency Doppler shift, the round-trip propagation time of a ranging signal, and the reception of signals suitable for long baseline interferometry. The measurements must be made with a degree of precision that satisfies navigation requirements. Measurement accuracy is affected by variations in velocity of propagation, knowledge of station location, timing precision, and electronic circuit delay in earth and space station equipment. Table 2 lists a current example of the requirements for navigation accuracy and the associated measurements.

TABLE 2

Navigation and tracking accuracy requirements

Parameter	Value
Navigation accuracy (m)	300 (at Jupiter)
Doppler measurement accuracy (Hz)	± 0.0005
Range measurement accuracy (m)	± 0.15
Accuracy of earth station location (m)	± 1

2.3.2 Radio science

Spacecraft telecommunication links can also be important to studies of propagation, relativity, celestial mechanics and gravity. Amplitude, phase, frequency, polarization and delay measurements provide the needed information. The opportunity to make these measurements depends upon the availability of appropriate allocations. Above 1 GHz, transmission delay and Faraday rotation (charged particle and magnetic field effects) decrease rapidly with increasing frequency, and thus are best studied with the lower frequencies. The higher frequencies provide relative freedom from these effects and are more suitable for studies of relativity, gravity and celestial mechanics. For these studies, calibration of charged particle effects at the lower frequencies is also needed.

Range measurements with an absolute accuracy of 1 or 2 cm are required for this fundamental scientific work. This accuracy depends upon wideband codes and the simultaneous use of multiple frequencies for charged-particle calibration.

2.4 Special requirements for manned deep-space missions

The functional requirements for such missions will be similar in kind to those for unmanned missions. The presence of human occupants in spacecraft will, however, place additional requirements for reliability on the telemetering, telecommand and tracking functions. Given the necessary level of reliability, the significant difference between manned and unmanned missions will be the use of voice and television links for both Earth-to-space and space-to-Earth radiocommunication. Data rates for these functions are shown in Table 1.

From a telecommunication standpoint, the effect of these additional functions will be a required expansion of transmission bandwidth in order to accommodate the video signals. Given the necessary link reliability and performance needed to support the required data transfer rates, telecommunications for manned and unmanned deep-space research are similar.

3 Technical characteristics

3.1 Locations and characteristics of deep-space earth stations

Table 3 gives the locations of earth stations with the capability of operating within bands allocated for deep-space research.

TABLE 3

Location of deep-space earth stations

Administration	Location	Latitude	Longitude
China	Kashi Jiamusi	38° 55' N 46° 28' N	75° 52' E 130° 26' E
European Space Agency	Cebreros (Spain) Malargüe (Argentina) New Norcia (Australia)	40° 27' N 35° 46' S 31° 20' S	4° 22' W 69° 22' W 116° 11' E
Germany	Weilheim	47° 53' N	11° 04' E
Ukraine	Evpatoriya	45° 11' N	33° 11' E
Russia	Medvezhi ozera Ussuriisk	55° 52' N 44° 01' N	37° 57' E 131° 45' E
Japan	Usuda, Nagano	36° 08' N	138° 22' E
United States	Canberra (Australia) Goldstone, California (United States) Madrid (Spain)	35° 28' S 35° 22' N 40° 26' N	148° 59' E 115° 51' W 4° 17' W

At each of these locations there are one or more antennas, receivers and transmitters that can be utilized for deep-space links in one or more of the allocated bands. The principal parameters that characterize the maximum performance of one or more of these stations are listed in Table 4. Although these characteristics do not apply to all stations, it is nevertheless essential that band allocations and criteria for protection from interference be based on the maximum performance available. This is required in order to provide for international operation and protection of deep-space missions.

TABLE 4

Characteristics of deep-space earth stations with 70 m antennas

Frequency (GHz)	Antenna gain (dBi)	Antenna beamwidth (degrees)	Transmitter power (dBW)	e.i.r.p. (dBW)	Receiving system noise temperature (K)	Receiving system noise power spectral density (dB(W/Hz))
2.110-2.120 Earth-to-space	62	0.14	50 56(1)	112 118(1)	--	--
2.290-2.300 Space-to-Earth	63	0.13	--	--	25(2) 21(3)	–214(2) –215(3)
7.145-7.190 Earth-to-space	72	0.04	43	115	--	--
8.400-8.450 Space-to-Earth	74	0.03	--	--	37(2) 27(3)	–213(2) –214(3)
31.832.3 Space-to-Earth	83.6(4)	0.01(4)	--	--	83(2) (4) 61(3) (4)	–209(2) (4) –211(3) (4)
34.2-34.7 Earth-to-space	84(4)	0.01(4)	To be determined	To be determined	--	--

(1) 56 dBW transmitter power used only during spacecraft emergencies.

(2) Clear weather, 30° elevation angle, duplex mode for simultaneous transmission and reception.

(3) Clear weather, 30° elevation angle, receive only.

(4) Estimate.

The receiving performance of deep-space earth stations is usually specified in terms of the ratio of signal energy per bit-to-noise spectral density required to give a particular bit error rate. Another way to show the high performance and sensitivity of these stations is to express the ratio of antenna gain-to-noise temperature. This quotient, commonly referred to as *G*/*T*, is approximately 50 dB/(K) at 2.3 GHz, and 59.5 dB/(K) at 8.4 GHz. These values may be compared with the lower and typical 41 dB/(K) of some fixed satellite earth stations.

3.2 Space stations

Spacecraft size and weight is limited by the payload capability of the launch vehicle. The power of the space station transmitter and the size of the antenna are limited in comparison with those parameters at earth stations. The noise temperature of the receiver is higher because an uncooled preamplifier is generally used.

The space station has a combined receiver-transmitter, called a transponder, which operates in one of two modes. In the turn-around (also called two-way) mode, the carrier signal received from an earth station is used to control the oscillator in a phase-locked signal loop. The frequency of this oscillator is then used to control the transmitter frequency of the transponder according to a fixed ratio. In the one-way mode, no signal is received from an earth station, and the spacecraft transmitter frequency is controlled by a crystal oscillator.

In the two-way mode, the spacecraft transmitted frequency and phase is controlled very precisely because of the extreme accuracy and precision of the signal received from an earth station.

Table 5 lists major characteristics that are typical of space stations designed for deep-space research.

TABLE 5

Characteristics typical of space stations for deep-space research

Earth-to-space frequency (GHz)	Antenna diameter (m)	Antenna gain (dBi)	Antenna beamwidth (degrees)	Receiver noise temperature (K)	Receiver noise spectral power density (dB(W/Hz))
2.110-2.120	3.7	36	2.6	200	–206
7.145-7.190	3.7	48	0.64	330	–203
34.2-34.7	3.7	61	0.14	2 000	−196

Space-to-Earth frequency (GHz)	Antenna diameter (m)	Antenna gain (dBi)	Antenna beamwidth (degrees)	Transmitter power (dBW)	e.i.r.p. (dBW)
2.290-2.300	3.7	37	2.3	13	50
8.400-8.450	3.7	48	0.64	13	61
31.8-32.3	3.7	59.5	0.17	13	72.5

Because of the limited e.i.r.p. of space stations, the earth station must have the most sensitive receiver possible. Receivers with lower sensitivity may be used in space stations as a result of the very high e.i.r.p. of the earth station. Data rate requirements and considerations of size, weight, cost, complexity and reliability determines the receiver noise temperature needed for a particular spacecraft.

The power of the space station transmitter is limited primarily by the electrical power that can be supplied by the spacecraft.

4 Deep-space telecommunication methods

Telemetering and telecommand functions for deep-space telecommunications are typically accomplished by transmission of phase modulated carriers. Doppler tracking is done by phase coherent detection of the received carrier. By adding a ranging signal to the modulation, the ranging function may be performed.

4.1 Carrier tracking and Doppler measurement

As received on Earth, the frequency of a signal transmitted by the spacecraft is modified by the Doppler effect. The means to measure the Doppler shift, and hence the velocity of the spacecraft with respect to the earth station, is provided by carrier phase tracking. Earth and space station receivers track the carrier signal with a phase-locked loop or a Costas loop. In the two-way transponder mode, the frequency and phase in the space station phase-locked loop are used to develop one or more space-to-Earth frequencies. This provides signals to the earth station that are correlated with the Earth-to-space frequency, enabling precise Doppler measurements to be made.

In the one-way mode, the space-to-Earth frequencies are derived from the oscillator in the transponder, and the Doppler measurement is based on *a priori* knowledge of the oscillator frequency.

4.2 Modulation and demodulation

The radio links use phase modulation of the radio-frequency carrier. The baseband digital data signal is used to modulate a subcarrier, which in turn phase modulates the radio-frequency carrier. A square wave sub-carrier is typically used for telemetering; for telecommand the sub-carrier is often sinusoidal. The modulation index is adjusted to provide a desired ratio of residual carrier power to data sideband power. This ratio is selected to provide optimum carrier tracking and data detection in the receiver.

RF carrier and data sub-carrier demodulation is accomplished by phase-locked loops (PLLs). Data detection generally uses correlation and matched filter techniques.

Television and voice links for manned missions may use other modulation and demodulation techniques. Typically, bandwidth-efficient (offset) QPSK and GMSK modulation and demodulation are used in these cases with carrier tracking accomplished via Costas loops instead of PLLs.

4.3 Coding

In a digital telecommunication link, error probability can be reduced if the information bandwidth is increased. Coding accomplishes this increase by translating each data bit into a larger number of code symbols in a particular way. Some examples of coding types are block and convolutional codes. After transmission, the original data are recovered by a decoding process that is matched to the code type. The performance advantage of coded transmission is related to the wider bandwidth, and can vary from to 3.8 dB (convolutional coding, bit error ratio of 1×10^{-3}) to more than 9 dB (rate 1/6 turbo coding).

4.4 Multiplexing

Science and maintenance telemetering may be combined into a single digital data stream by time division multiplexing; or may be on separate sub-carriers that are added to provide a composite modulating signal. A ranging signal may also be added in combination with telemetering or telecommand. The amplitude of the different data signals is adjusted to properly divide the transmitter power between the carrier and the information sidebands.

4.5 Ranging

Ranging is performed from an earth station using the space station transponder in the two-way mode. Ranging modulation on the Earth-to-space signal is recovered in the transponder and used to modulate the space-to-Earth carrier. At the earth station, comparison of the transmitted and received ranging codes yields a transmission delay measurement proportional to range.

A fundamental limitation to ranging precision is the ability to measure time correlation between the transmitted and received codes. The system currently in use employs a highest code frequency of 2 062 MHz. The code period is 0.485 μs and resolution to 4 ns is readily achieved, assuming sufficient signal-to-noise ratio. This resolution is equivalent to 120 cm in a two-way path length, 60 cm in range. This meets the current navigation accuracy requirements of Table 2.

For the 1 cm accuracy needed for future radio science experiments (see § 2.3.2) a code frequency of at least 30 MHz is required.

4.6 Antenna gain and pointing

For the parabolic antennas typically used in space research, the maximum gain is limited by the accuracy with which the surface approaches a true parabola. This latter limitation places a bound on the maximum frequency that may be effectively used with a particular antenna.

One factor in surface accuracy, common to both earth and space station antennas, is manufacturing precision. For earth station antennas, additional surface deformation is caused by wind and thermal effects. As elevation angle is varied, gravity introduces distortion of the surface, depending on the stiffness of the supporting structure.

For space station antennas, size is limited by permissible mass, by the space available in the launch vehicle, and by the state of the art in the construction of unfurlable antennas. Thermal effects cause distortion in space station antenna's surfaces.

The maximum usable gain of antennas is limited by the ability to point them accurately. The beamwidth must be adequate to allow for the angular uncertainty in pointing. All the factors that cause distortion of the reflector surface also affect pointing accuracy. The accuracy of the spacecraft attitude control system (often governed by the amount of propellant which can be carried) is a factor in space station antenna pointing.

The precision with which the location of the earth and space stations are known with respect to each other affects the minimum usable beamwidth and the maximum usable gain.

Table 6 shows typical limits on antenna performance.

TABLE 6

Current limitations on accuracy and maximum antenna gain

Limiting parameter	Space station antennas		Earth station antennas	
	Typical maximum value of parameter	Maximum gain	Typical maximum value of parameter	Maximum gain
Accuracy of dish surface	0.24 mm r.m.s., 3.7 m dish	66 dBi[(1)] at 100 GHz	0.53 mm r.m.s., 70 m dish	83 dBi[(1)] at 37 GHz
Pointing accuracy	± 0.15° (3σ)	55 dBi[(2)]	± 0.005° (3σ)	75 dBi[(2)]

(1) Gain at other frequencies will be lower.

(2) Gain of antenna with half power beamwidth equal to 2 times pointing accuracy. The beamwidth of an antenna with higher gain will be too narrow with respect to pointing accuracy.

4.7 Additional radionavigation techniques

Doppler and ranging measurements provide the basic tracking information needed for navigation. Additional techniques have been developed to enhance navigation accuracy.

4.7.1 Calibration of the velocity of propagation as affected by charged particles

Range and Doppler measurements are influenced by variations in the velocity of radio-wave propagation caused by free electrons along the transmission path. The electrons exist in varying densities in space and in planetary atmospheres, and are particularly dense near the Sun. Unless accounted for, these variations in propagation velocity can introduce errors in navigation calculations.

The charged particles cause an increase in phase velocity and a decrease in group velocity. By comparing range change with integrated Doppler over a period of time, the charged particle effect may be determined. The effect on propagation velocity is inversely proportional to the square of the radio frequency. This frequency dependency may be used for additional calibration accuracy. Turnaround ranging and Doppler tracking can be performed with simultaneous space-to-Earth signals in two or more separate bands. The charged particle effects in the separate bands are different in magnitude, and this difference is used to improve the calibration.

The charged particle effect and its affect on range measurement is given in Report ITU-R SA.2177.

4.7.2 Very long baseline interferometry (VLBI)

Accuracy of spacecraft navigation depends upon the precise knowledge of earth station location with respect to the navigation coordinate system. A 3 m error in the assumed station location can result in a 700 km error in the calculated position of a spacecraft at Saturn distance. VLBI provides a means of improving the estimate of station location by using a celestial radio source (quasar) as a signal source at an essentially unchanging point on the celestial sphere. It is possible to record the quasar signals in such a way as to determine, with great accuracy, the difference in time of reception at two widely separated stations. Using several of these measurements the station locations can be determined to a relative accuracy of 10 cm. Frequencies near 2 and 8 GHz are used for VLBI at the present time.

The VLBI technique is also used to measure directly the spacecraft declination angle. Two accurately located earth stations separated by a large north/south distance, measure the range to the spacecraft. The declination can then be calculated with great precision.

A third application of the VLBI method can be used to improve the accuracy of measurement of spacecraft angular position. Two or more earth stations alternately observe a spacecraft signal and a quasar signal. By knowing time, station location and the effect of Earth rotation on the received signals, the angular position of the spacecraft can be determined with respect to the celestial references. When fully developed the techniques will provide a significant improvement over the current accuracy of 0.01 arc second. The improved accuracy will permit more precise navigation.

5 Performance analysis and design margins

Table 7 shows a link budget used for performance analysis. The example given is for high rate telemetering from Jupiter. Similar analysis for telecommand and ranging is performed. The earth and space station characteristics shown earlier are used as the basis for calculating a performance margin for each telecommunication function.

TABLE 7

Performance budget, spacecraft-to-Earth from Jupiter

Mission: Voyager Jupiter/Saturn 1977 **Mode: Telemetering, 115.2 kbit/s, coded, 8.45 GHz carrier**	
Transmitter parameters	
RF power (21 W) (dBW)	13.2
Circuit loss (dB)	–0.2
Antenna gain (3.7 m) (dBi)	48.1
Pointing loss (dB)	–0.2
Path parameters	
Free space loss between isotropic antennas (dB) (8.45 GHz, 9.3×10^8 km)	–290.4
Receiver parameters	
Antenna gain (64 m, 30° elevation angle) (dBi)	72.0
Pointing loss (dB)	–0.3
Weather attenuation (dB)	–0.1
System noise power spectral density (22.6 K) (dB(W/Hz))	–215.1
Total power summary	
Link loss (dB)	–171.1
Received power $P(T)$ (dBW)	–157.9
Carrier tracking performance (two-way)	
Carrier power/total power (dB)	–15.4
Received carrier power (dBW)	–173.3
Carrier threshold noise bandwidth (B = 10 Hz) (10 log B)	10.0
Noise power (dBW)	–205.1
Threshold signal/noise (dB)	20
Threshold carrier power (dBW)	–185.1
Performance margin (dB)	11.8
Data detection performance	
Data power/total power (dB)	–0.3
Data reception and detection losses (dB)	–0.5
Received data power (dBW)	–158.7
Noise bandwidth (effective noise bandwidth for matched filter detection of 115.2 kbit/s data) (dB)	50.6
Noise power (dBW)	–164.5
Threshold signal/noise (5×10^{-3} bit error rate) (dB)	2.3
Threshold data power (dBW)	–162.2
Performance margin (dB)	3.5

A most important point in the design of deep-space missions is that the telemetering performance margin is quite small (3.5 dB in the example given). This small margin is a consequence of the need to obtain maximum scientific value from each spacecraft. To design with a 10 dB larger margin of safety would reduce the quantity of telemetered data by a factor of 10. The risk of using a system with small performance margin is its susceptibility to harmful interference, and for bands above 2 GHz, decreased reliability caused by weather effects.