RECOMMENDATION ITU-R SA.1012*

Preferred frequency bands for deep-space research in the 1-40 GHz range

(Question ITU-R 133/7)

(1990-1994)

The ITU Radiocommunication Assembly,

considering

a) that frequencies most suited for telecommunications between the Earth and spacecraft in deep space are determined partly by atmospheric and interplanetary propagation phenomena;

b) that technology also influences the selection of preferred frequencies;

c) that requirements for telecommunication reliability must be satisfied during periods of adverse atmospheric effects;

d) that the same frequency may be used for spacecraft at different celestial coordinates, but that different spacecraft in the vicinity of the same coordinates and within the beamwidth of an earth station antenna will usually require different frequencies;

e) that it is practical and desirable to effect telemetering and tracking functions on the same space-to-Earth link, and telecommand and tracking functions on the same Earth-to-space link;

f) that for precision Doppler tracking, a pair of coherently related Earth-to-space and space-to-Earth frequencies is required;

g) that for more accurate calibration of the effects of charged particles on the velocity of propagation, simultaneous use of links with coherent frequencies in two or more widely separated bands is required;

h) that voice and video links associated with manned spacecraft in deep space could use frequency bands allocated for telemetering, telecommand and tracking functions;

j) that preferred frequency ranges have been developed and are shown in Annex 1;

k) that the feasibility of band allocations for deep-space research depends, *inter alia*, on sharing with other services,

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* Radiocommunication Study Group 7 made editorial amendments to this Recommendation in 2003 in accordance with Resolution ITU-R 44.

recommends

1 that between 1 and 40 GHz, band allocations for deep-space research be selected from the preferred frequency ranges given in Table 3;

2 that the contents of § 6 of Annex 1 and the bandwidth requirements of Recommendation ITU-R SA.1015 be taken into account;

3 that the feasibility of sharing with other services be considered (see Recommendation ITU-R SA.1016).

Annex 1

Selection of frequency bands in the 1-40 GHz range that are preferred for deep-space research

1 Introduction

Telecommunication link performance, equipment characteristics and mission requirements determine the frequency bands that are preferred for deep-space research. This Annex presents an analysis that leads to the selection of preferred frequency bands. For information on general mission requirements and equipment considerations, see Recommendation ITU-R SA.1014; for information on required bandwidths see Recommendation ITU-R SA.1015.

The objective of identifying preferred frequency bands is to provide the technical basis for band allocations from which the designer can select operating frequencies best suited to mission requirements.

2 Criteria for selection of preferred frequency bands

For each telecommunication function, i.e., maintenance and science telemetering, telecommand, tracking and radio science, there is a frequency band, or set of frequency bands, which will provide best performance. Best performance may be expressed in terms of lowest error rate, highest measurement accuracy, maximum data rate, best link reliability, or some combination of these parameters. The best performance that is obtainable at a particular time with a particular system depends upon the characteristics of radio-wave propagation.

A convenient index of best performance is the ratio of received signal power to noise power spectral density ratio P_r/N_0. The frequency band which provides the highest value of P_r/N_0 for a particular system and propagation conditions is defined as a preferred frequency band.

For this Annex, analysis of the variation in P_r/N_0 as a function of frequency was in accordance with Recommendation ITU-R SA.1017. From the resulting data, frequency ranges that provide optimum performance for the assumed conditions may be identified.

3 Equipment characteristics that concern link performance analysis

3.1 Antenna considerations

Earth stations for deep-space research typically employ large steerable parabolic antennas which are expensive and infrequently constructed. A mission designer is generally not free to consider a range of earth station antenna diameters when selecting frequencies. For this reason, the analysis considers the earth station antenna to have a fixed diameter. The gain and beamwidth of this antenna are a function of frequency.

For space stations, the designer may consider a variety of antenna types and sizes. The analysis accounts for this freedom by considering two cases: a parabolic reflector antenna with a fixed diameter and whose beamwidth and gain are a function of frequency and an antenna whose beamwidth (gain) does not vary with frequency.

The fixed diameter case may be applied over the frequency range to be considered if the diameter is small enough (beamwidth at highest frequency is wide enough) so that the antenna pointing accuracy does not limit the minimum beamwidth.

The fixed beamwidth (fixed gain) case arises when antenna pointing accuracy determines the minimum beamwidth, or when the antenna must give very wide coverage to permit communication without regard to space station attitude. An omnidirectional antenna is an example of the fixed beamwidth case.

Link analysis in this Annex assumes that a fixed diameter antenna for a space station is 60% efficient and has a gain which increases directly as the frequency squared. For the fixed beamwidth (fixed gain) case the gain is assumed to be 0 dBi and independent of frequency.

The earth station antenna gain used in the analysis is taken from Recommendation ITU-R SA.1014.

3.2 Transmitter power

For space station transmitters, the RF output power depends on the amount of primary power that can be provided by the spacecraft and is further limited by transmitter efficiency. For earth stations these limitations are much less significant.

For link performance analysis in this Annex, transmitter power is considered to be independent of frequency.

3.3 Receiving equipment noise temperature

The space station receiving system noise temperature is dominated by the input preamplifier and associated pre-selection filter. Antenna feedline losses are relatively unimportant in their noise contribution. The space station noise temperature used in this Annex is representative of current technology utilizing uncooled solid state devices.

At earth stations there is no important size, weight or complexity limitation and the most sensitive possible receiver is needed. Cryogenically cooled MASER preamplifiers are commonly used. Link analysis in this Annex assumes that the earth station noise temperatures are as shown in Recommendation ITU-R SA.1014.

4 Propagation considerations

Analysis of link performance requires assumptions about propagation conditions. A critical assumption is the rain rate and resulting attenuation. For low noise receiving systems typical of deep-space research, particularly the earth station receivers, even a small increase in attenuation caused by rain results in a significant reduction in P_r/N_0. This is because the increase in sky noise is several times as large as the receiver noise temperature and therefore dominates the overall system noise temperature.

The analysis for this Annex assumes a rain rate of 10 mm/h (the amount exceeded 0.1% of the time at an earth station near Madrid, Spain).

Although this rate results in only 1 dB of attenuation compared to the clear air case at 8.4 GHz, 30° elevation angle, it causes a 5.8 dB degradation in the space-to-Earth P_r/N_0. As a result of the sensitivity of system performance (P_r/N_0) to small changes in attenuation along the propagation path, the performance curves shown later are strongly influenced by the assumed rain rate.

5 Results of performance analysis

The variation of P_r/N_0 shown in Figs. 1 to 4 was determined by the method of Recommendation ITU-R SA.1017 for the following assumed set of equipment characteristics and operating conditions:

Communication distance: 8×10^8 km

Diameter of earth station antenna: 70 m

Power of earth station transmitter: 100 kW

Diameter of space station antenna: 3.7 m

Power of space station transmitter: 25 W

The important features of the performance curves are the location of maxima and the effects of elevation angle and weather. The absolute values of P_r/N_0 depend upon the assumed link parameters. Different assumptions about communication distance, antenna characteristics and transmitter power would alter the absolute values but would not change the shape of the curves.

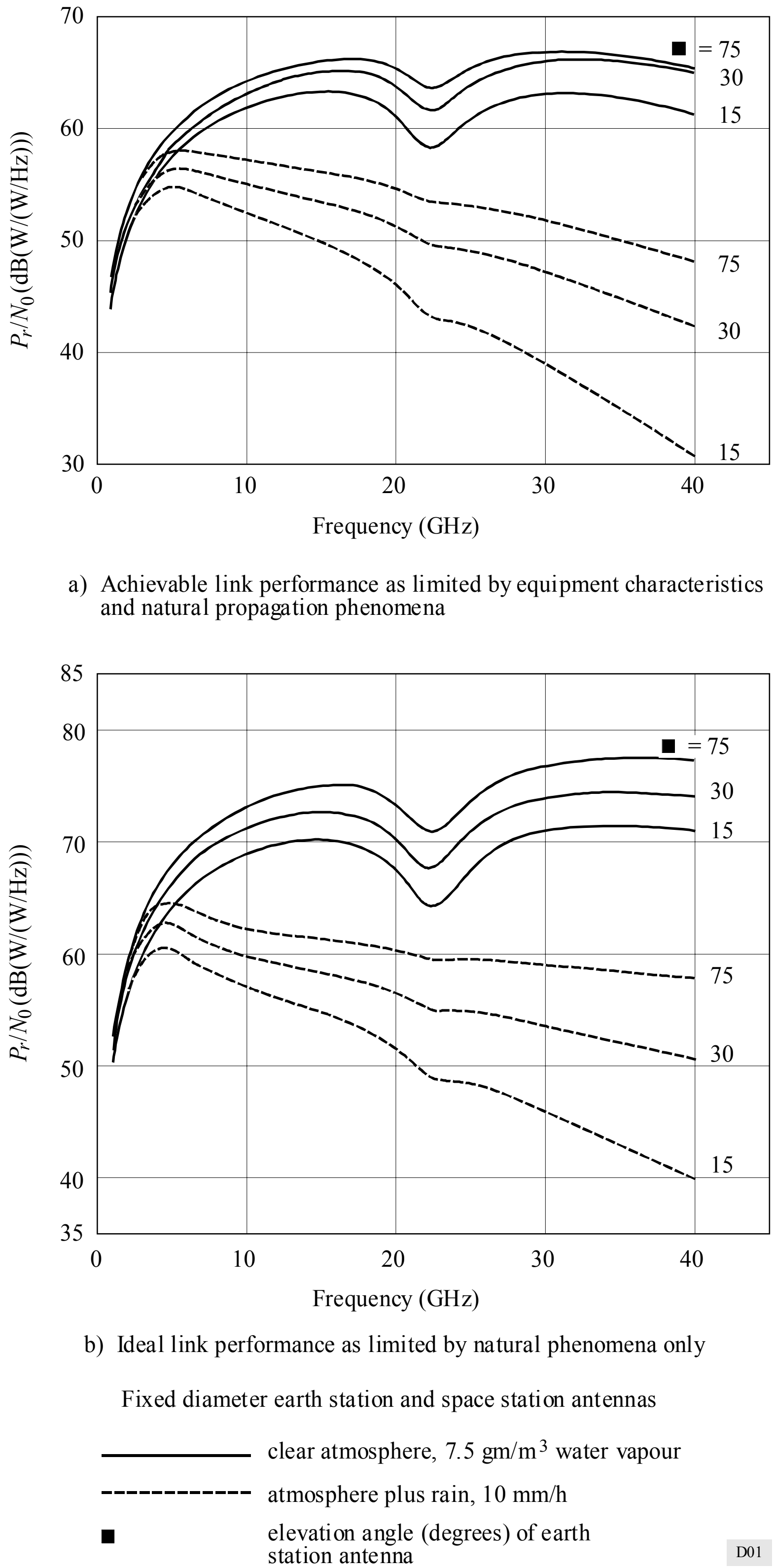
The figures show curves for clear and rainy weather and for earth station antenna elevation angles of 15°, 30° and 75° above the horizon. Figures 1a), 2a), 3a) and 4a) reflect the limitations imposed by typical equipment of earth and deep-space stations.

Figures 1b), 2b), 3b) and 4b) assume the use of perfect antennas and noiseless receivers. These curves illustrate performance as limited only by natural phenomena. Comparison of the a) and b) curves in each figure shows the potential for better link performance that could result from improvement of equipment technology.

Tables 1 and 2 show optimum frequency ranges for an indicated antenna configuration and weather condition. The criterion for selecting a frequency range was performance (P_r/N_0) within approximately 1 dB of the maximum available.

FIGURE 1

Space-to-Earth link performance, (P_r /N_0)

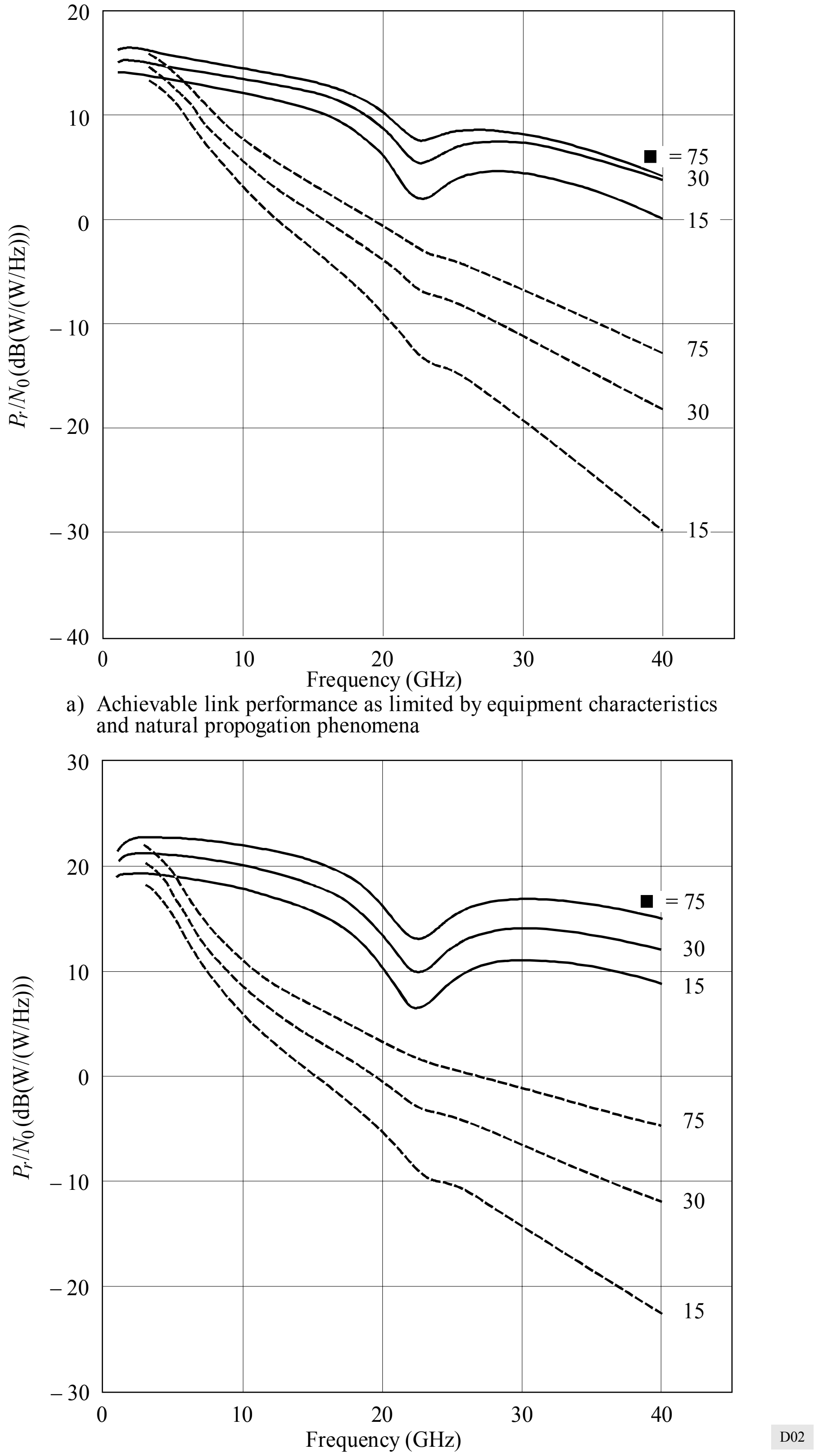


a) Achievable link performance as limited by equipment characteristics and natural propagation phenomena

b) Ideal link performance as limited by natural phenomena only

FIGURE 2

Space-to-Earth link performance, (P_r / N_0)



b) Ideal link performance as limited by natural phenomena only

Fixed diameter earth station antenna, fixed gain space station antenna

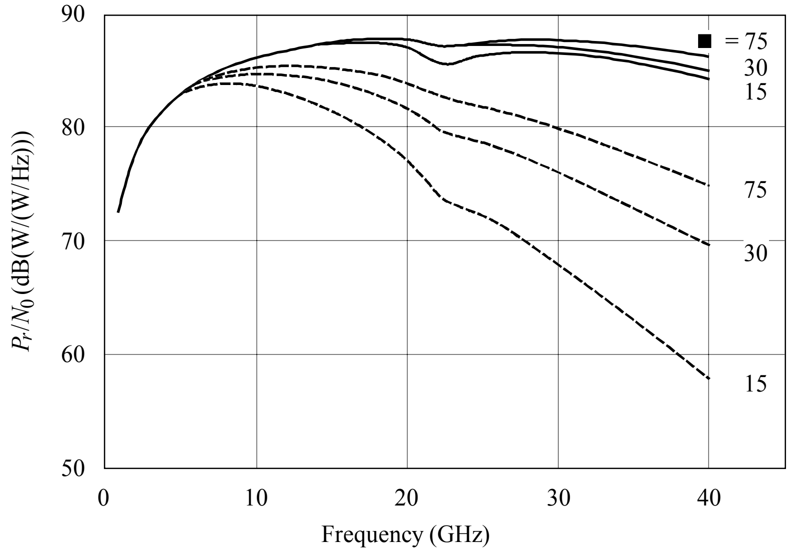
———— clear atmosphere, 7.5 gm/m^3 water vapour

- - - - - - atmosphere plus rain, 10 mm/h

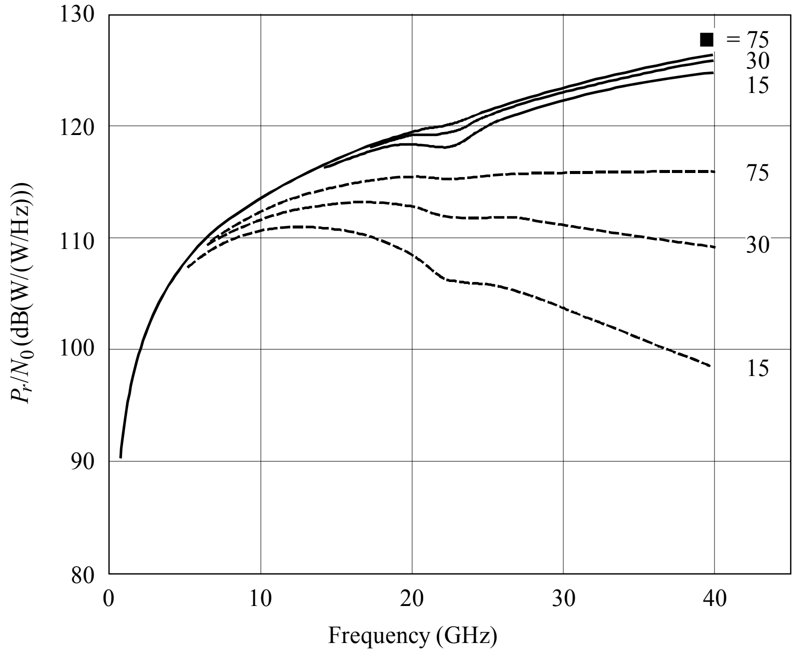
■ elevation angle (degrees) of earth station antenna

FIGURE 3

Earth-to-space link performance, (P_r/N_0)



a) Achievable link performance as limited by equipment characteristics and natural propagation phenomena



b) Ideal link performance as limited by natural phenomena only

Fixed diameter earth station and space station antennas

———— clear atmosphere, 7.5 gm/m^3 water vapour

- - - - - - atmosphere plus rain, 10 mm/h

■ elevation angle (degrees) of earth station antenna

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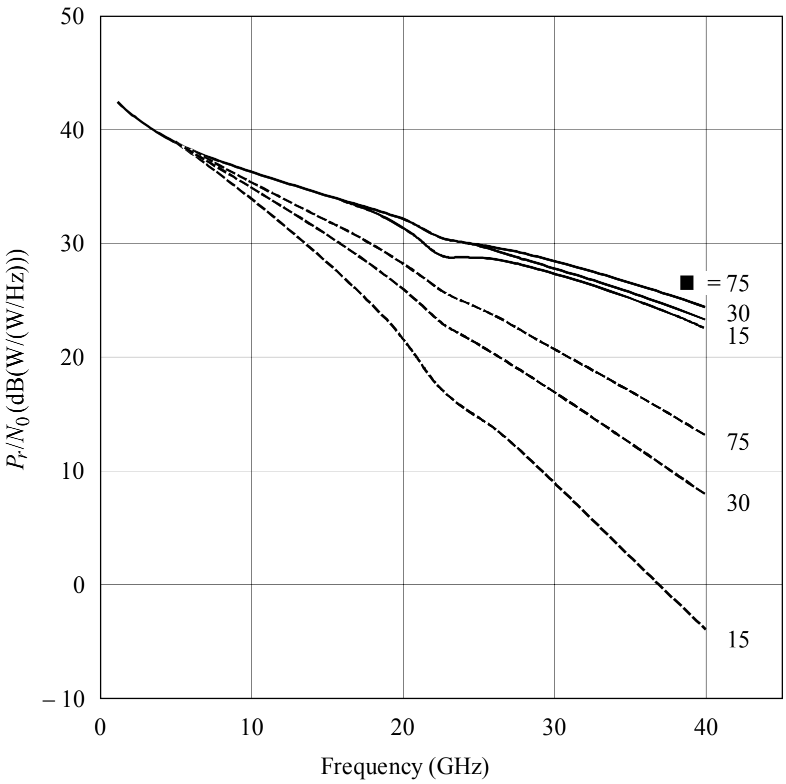
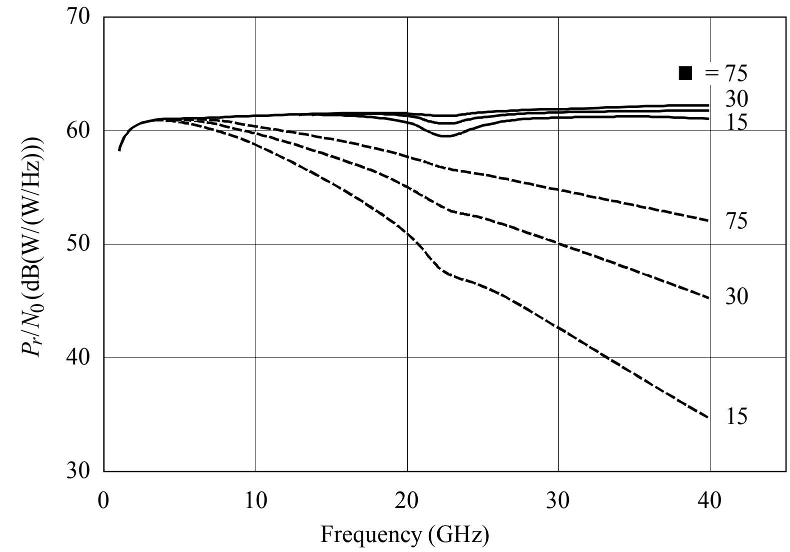
FIGURE 4

Earth-to-space link performance, (P_r/N_0)



a) Achievable link performance as limited by equipment characteristics and natural propagation phenomena



b) Ideal link performance as limited by natural phenomena only

Fixed diameter earth station antenna, fixed gain space station antenna

———————— clear atmosphere, 7.5 gm/m^3 water vapour

------------ atmosphere plus rain, 10 mm/h

■ elevation angle (degrees) of earth station antenna

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TABLE 1

Preferred frequency ranges: space-to-Earth

Antenna configuration	Weather	Range of preferred frequencies	
		Ideal equipment(1)	Current equipment(2)
Fixed diameter transmit	Clear	11.5-19 GHz 28.5-40 GHz	12-20 GHz 26-39.5 GHz
Fixed diameter receive	Rain	3 000-6 500 MHz	3 500-9 000 MHz
Fixed gain transmit	Clear	1 000-9 500 MHz	1 000-6 500 MHz
Fixed diameter receive	Rain	1 000-3 500 MHz	1 000-4 000 MHz

(1) Based on analysis that considers only natural phenomena.

(2) Based on analysis that includes the effect on equipment characteristics.

TABLE 2

Preferred frequency ranges: Earth-to-space

Antenna configuration	Weather	Range of preferred frequencies	
		Ideal equipment(1)	Current equipment(2)
Fixed diameter transmit	Clear	35-40 GHz	11.5-35.5 GHz
Fixed diameter receive	Rain	11-22 GHz	6 000 MHz-16 GHz
Fixed diameter transmit	Clear	2 000 MHz-40 GHz	1 000-2 000 MHz
Fixed gain receive	Rain	1 500-9 500 MHz	1 000-2 000 MHz

(1) Based on analysis that considers only natural phenomena.

(2) Based on analysis that includes the effect on equipment characteristics.

6 Selection of preferred frequency bands

Table 3 lists preferred frequency ranges as determined by link performance analysis and the following additional considerations.

6.1 Diplexer characteristics

Because of practical limits of wave polarizers and diplexers, simultaneous transmission and reception with a single antenna requires that the uplink and downlink frequencies be separated by approximately 8 to 20%. Pairs of bands chosen from the ranges listed in Table 3 must take this into account.

6.2 Link and allocation bandwidth

The bandwidth required for a particular telecommunication link and the estimated number of separate links provide an indication of needed allocation width. Recommendation ITU-R SA.1015 discusses bandwidth requirements.

TABLE 3

Gammes de fréquences préférées et leur application*

Frequency range (GHz)	Application
1-2	Earth-to-space links using the spacecraft wide beam low-gain antenna during clear or rainy weather. Used for uplink functions
1-4	Space-to-Earth links using the spacecraft wide beam low-gain antenna during rainy weather. Used for downlink functions
1-6.5	Space-to-Earth links using the spacecraft wide beam low-gain antenna during clear weather. Used for downlink functions
3.5-9	Space-to-Earth links using the spacecraft high-gain antenna during rainy weather. Used for downlink functions
6-16	Earth-to-space links using the spacecraft high-gain antenna during rainy weather. Used for uplink functions
11.5-35.5	Earth-to-space links using the spacecraft high-gain antenna during clear weather. Used for uplink functions
26-40	Space-to-Earth links using the spacecraft high-gain antenna during clear weather. Used for downlink functions

* Based on analysis that includes the effect of equipment characteristics and 30° elevation angle for the earth station antenna.

7 Requirement for several allocations that are widely spaced in the spectrum

Precise knowledge of the velocity of propagation is required to satisfy the requirements of radio science and spacecraft navigation. To determine the velocity of propagation it is necessary to account for the group delay caused by charged particles along the transmission path. The group delay measurement applies only to the particular spacecraft at a particular time.

If group delay caused by charged particles along the propagation path is not taken into account, there will be an error in range measurement, as discussed below.

In passing through an ionized medium the phase velocity of a radio signal is increased and the group velocity is decreased. The effect is proportional to the integrated electron density along the path, and inversely proportional to the square of the frequency.

The process of measuring the distance to a spacecraft by radio techniques is called ranging. Ranging is typically accomplished by measuring the time required for a radio signal to travel from an earth station to the spacecraft and be returned to Earth. The time includes the group delay caused by charged particles along the path. Unless the group delay is accounted for, the range measurement will be in error.

A principal source of group delay is the ionosphere of the Earth. Propagation through the ionosphere is discussed in Recommendation ITU-R P.531. An estimate of the upper limit of this delay is 0.25 μs at 1 GHz and 0.62 ns at 20 GHz.

The solar plasma in interplanetary space also causes group delay. Measurements made during past deep-space missions have provided group delay data leading to an approximation formula for electron density as a function of distance from the Sun:

$$N = 10^{12} \left[\frac{221}{r^6} + \frac{1.55}{r^{2.3}} \right]$$

where:

N: electron density (electrons/m^3)

r: distance from centre of the Sun, measured in Sun radii (radius of Sun = 6.96×10^8 m).

The group delay for a radio signal passing through interplanetary space is given by:

$$t = N_s \frac{1.34 \times 10^{-7}}{f^2}$$

where:

t: group delay caused by charged particles (s)

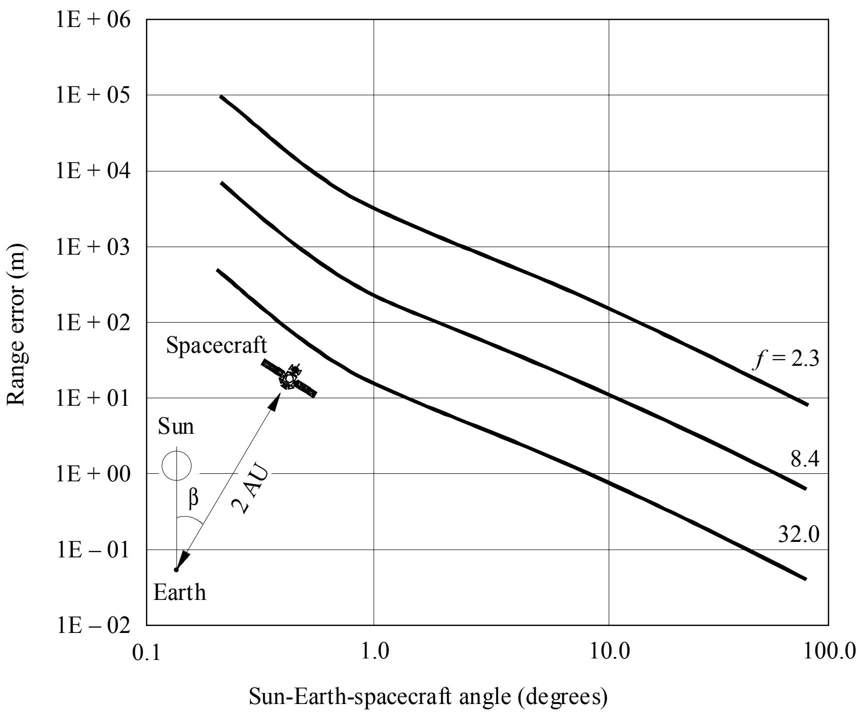
f: frequency (Hz)

N_s: total electrons per m^2 along the path.

Figure 5 shows an example of the range measurement error caused by solar plasma. The figure was obtained by assuming a path of 3×10^8 km, calculating the group delay as a function of frequency and angle from the Sun and then multiplying the delay by the speed of light to give a corresponding distance.

FIGURE 5

Range error from uncorrected group delay



f: frequency (GHz)
β: Sun-Earth-spacecraft angle
Sun-Earth distance = 1 AU
1 AU = 1.5×10^8 km

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The needed precision of group delay measurement may require the simultaneous use of links in two separate bands, preferably differing in frequency by at least a factor of four. The group delay between the two downlinks is different and this difference can be used to compute a suitable correction for the delay in each link. As an example of the use of separate bands, an uplink near 2 GHz may be used to provide a phase reference for simultaneous downlinks near 2 and 8 GHz. A downlink operating at a frequency above 20 GHz is relatively free of charged particle effects and can provide a particularly valuable reference for calibration of a link operating at a lower frequency.