

International Telecommunication Union

ITU-R
Radiocommunication Sector of ITU

Report ITU-R SA.2177
(10/2010)

**Selection of frequency bands
in the 1-120 GHz range for
deep-space research**

SA Series
Space applications and meteorology



International
Telecommunication
Union

Foreword

The role of the Radiocommunication Sector is to ensure the rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services, including satellite services, and carry out studies without limit of frequency range on the basis of which Recommendations are adopted.

The regulatory and policy functions of the Radiocommunication Sector are performed by World and Regional Radiocommunication Conferences and Radiocommunication Assemblies supported by Study Groups.

Policy on Intellectual Property Right (IPR)

ITU-R policy on IPR is described in the Common Patent Policy for ITU-T/ITU-R/ISO/IEC referenced in Annex 1 of Resolution ITU-R 1. Forms to be used for the submission of patent statements and licensing declarations by patent holders are available from <http://www.itu.int/ITU-R/go/patents/en> where the Guidelines for Implementation of the Common Patent Policy for ITU-T/ITU-R/ISO/IEC and the ITU-R patent information database can also be found.

Series of ITU-R Reports

(Also available online at <http://www.itu.int/publ/R-REP/en>)

Series	Title
BO	Satellite delivery
BR	Recording for production, archival and play-out; film for television
BS	Broadcasting service (sound)
BT	Broadcasting service (television)
F	Fixed service
M	Mobile, radiodetermination, amateur and related satellite services
P	Radiowave propagation
RA	Radio astronomy
RS	Remote sensing systems
S	Fixed-satellite service
SA	Space applications and meteorology
SF	Frequency sharing and coordination between fixed-satellite and fixed service systems
SM	Spectrum management

Note: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.

Electronic Publication
Geneva, 2010

© ITU 2010

All rights reserved. No part of this publication may be reproduced, by any means whatsoever, without written permission of ITU.

REPORT ITU-R SA.2177

**Selection of frequency bands in the 1-120 GHz range
for deep-space research**

(2010)

TABLE OF CONTENTS

		<i>Page</i>
1	Introduction	3
2	Selection of frequency bands in the 1-40 GHz range	3
2.1	Equipment characteristics that concern link performance analysis	3
2.1.1	Antenna sizes and gains	3
2.1.2	Transmitter power	4
2.1.3	Receiving equipment noise temperature	4
2.2	Propagation considerations	4
2.3	Results of performance analysis	4
2.4	Preferred frequency bands in the 1-40 GHz range	10
2.5	Requirement for several allocations that are widely spaced in the spectrum	11
3	Selection of frequency bands in the 40-120 GHz range	12
3.1	Advantages of higher frequencies	12
3.1.1	Increased link performance	13
3.1.2	Wider bandwidth	13
3.1.3	More accurate measurement of phase and group-delay	13
3.1.4	Shielding from terrestrial interference	13
3.2	Basis for frequency selection	13
3.3	Frequency-dependent characteristics of interplanetary propagation	13
3.3.1	Interplanetary attenuation	14
3.3.2	Interplanetary sky noise temperature	14
3.3.3	Sky noise temperature at earth stations	15
3.3.4	Velocity of interplanetary propagation	15
3.3.5	Interplanetary scintillation	15

	<i>Page</i>
3.4 Frequency-dependent characteristics of propagation through an atmosphere....	15
3.4.1 Atmospheric attenuation	15
3.4.2 Atmospheric scintillation	17
3.5 Frequency-dependent equipment factors	17
3.6 Example of link performance analysis	18
3.7 Preferred frequency bands in the 40-120 GHz range	19
4 Conclusions	19

1 Introduction

Telecommunication link performance, equipment characteristics and mission requirements determine the frequency bands that are preferred for deep-space research. This Report presents an analysis that leads to the selection of preferred frequency bands in the 1-120 GHz range. 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. Sections 2 and 3 of this Report give the technical basis for the selection of frequency bands in the 1-40 GHz and 40-120 GHz ranges.

2 Selection of frequency bands in the 1-40 GHz range

For each telecommunication function, i.e. maintenance and science telemetry, 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 bit error rate, highest measurement accuracy, maximum data rate, highest 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 (P_r/N_0). The frequency band which provides the highest value of P_r/N_0 ratio for a particular system and propagation conditions is defined as a preferred frequency band. From the resulting data, frequency ranges that provide optimum performance for the assumed conditions may be identified.

2.1 Equipment characteristics that concern link performance analysis

2.1.1 Antenna sizes and gains

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 band 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 Report 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.

2.1.2 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 Report, transmitter power is considered to be independent of frequency.

2.1.3 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 Report 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 Report assumes that the earth station noise temperatures are as shown in Recommendation ITU-R SA.1014.

2.2 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 Report 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 0.7 dB of attenuation compared to the clear air case at 8.4 GHz with 30° elevation angle, it causes a 5 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.

2.3 Results of performance analysis

The variation of P_r/N_0 shown in Figs 1 to 4 was determined by the method of Report ITU-R SA.2183 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: 20 kW
- Diameter of space station antenna: 3.7 m (Case 1: fixed diameter)
- Fixed gain of space station antenna: 0 dB (Case 2: fixed gain)
- 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) assume the use of perfect antennas and noiseless receivers. These curves illustrate performance as limited only by natural propagation phenomena. Figures 1b), 2b), 3b) and 4b) reflect the limitations imposed by typical equipment of earth and deep-space stations. 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.

FIGURE 1a)

**Ideal space-to-Earth link performance as limited only by natural propagation phenomena
(space station antenna = 3.7 m, earth station antenna = 70 m)**

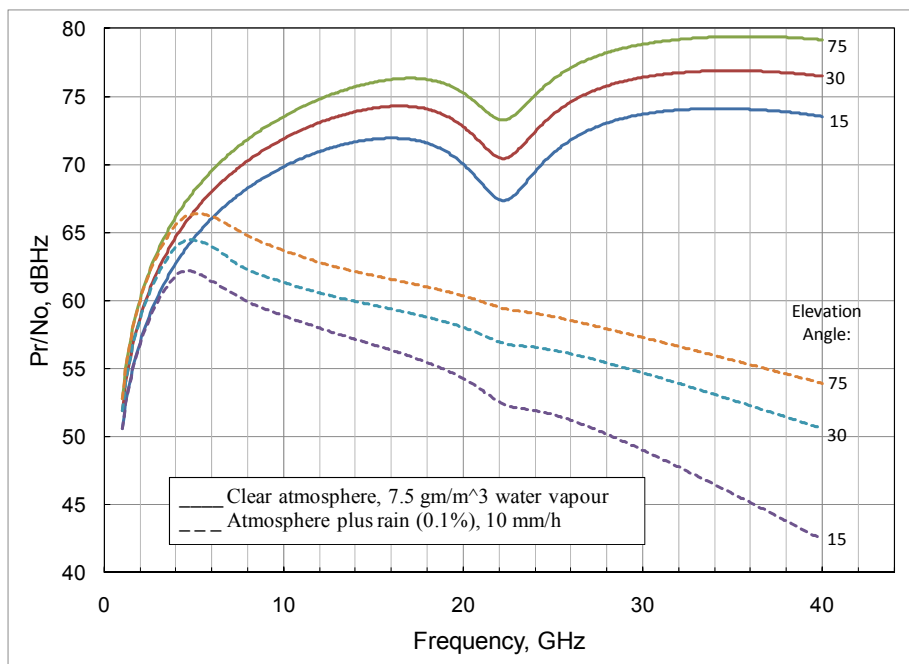


FIGURE 1b)

Achievable space-to-Earth link performance as limited by natural propagation phenomena and equipment characteristics
 (space station antenna = 3.7 m, earth station antenna = 70 m)

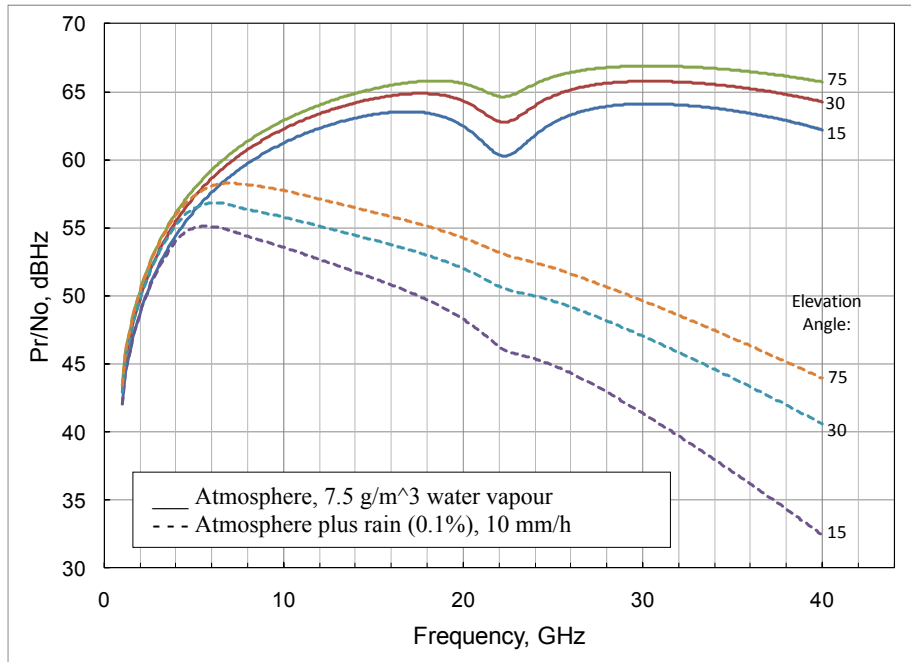


FIGURE 2a)

Ideal space-to-Earth link performance as limited only by natural propagation phenomena
 (space station antenna = 0 dB (fixed gain), earth station antenna = 70 m)

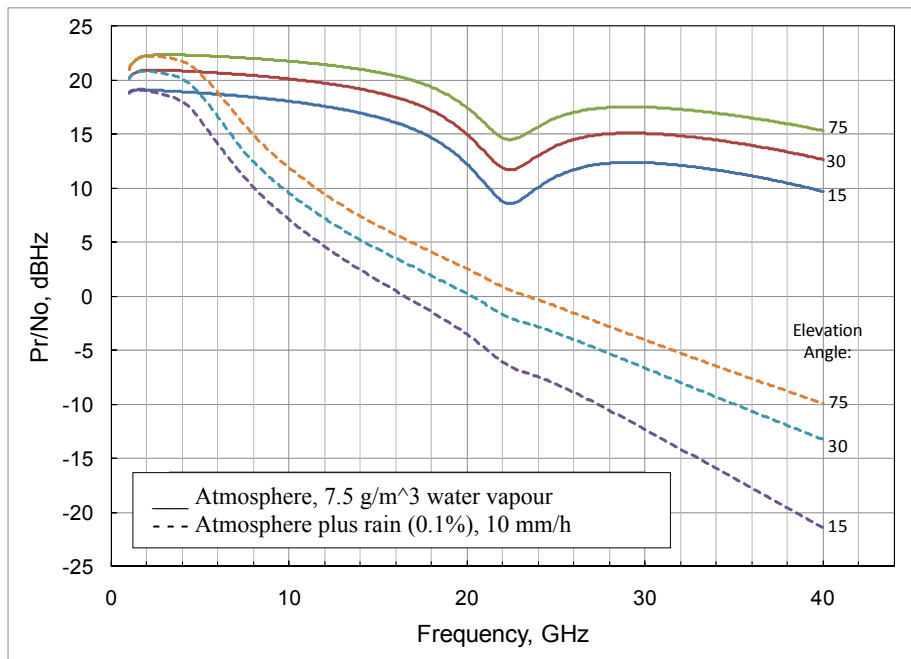


FIGURE 2b)

Achievable space-to-Earth link performance as limited by natural propagation phenomena and equipment characteristics
 (space station antenna = 0 dB (fixed gain), earth station antenna = 70 m)

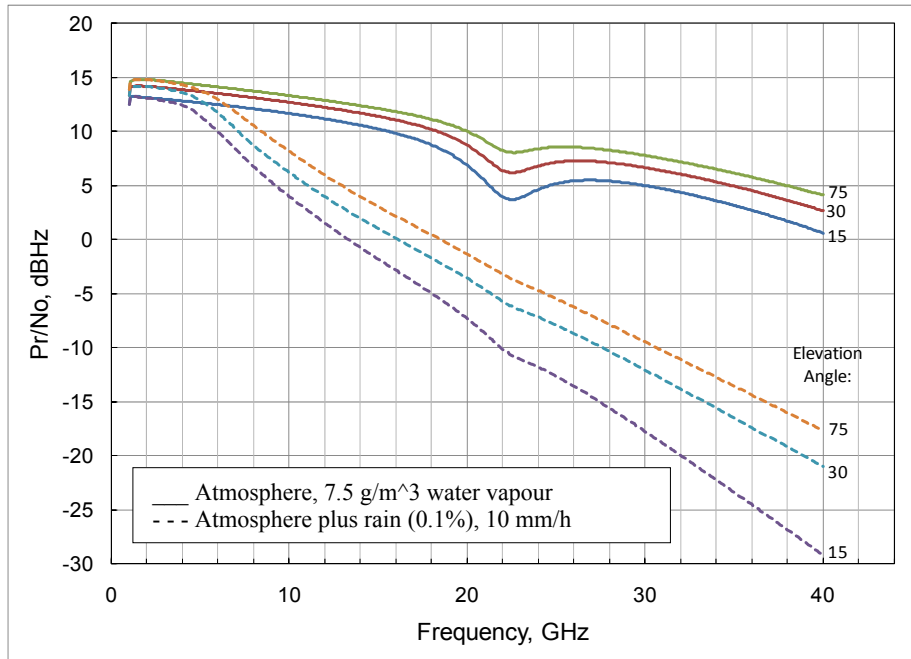


FIGURE 3a)

Ideal Earth-to-space link performance as limited only by natural propagation phenomena
 (earth station antenna = 70 m, space station antenna = 3.7 m)

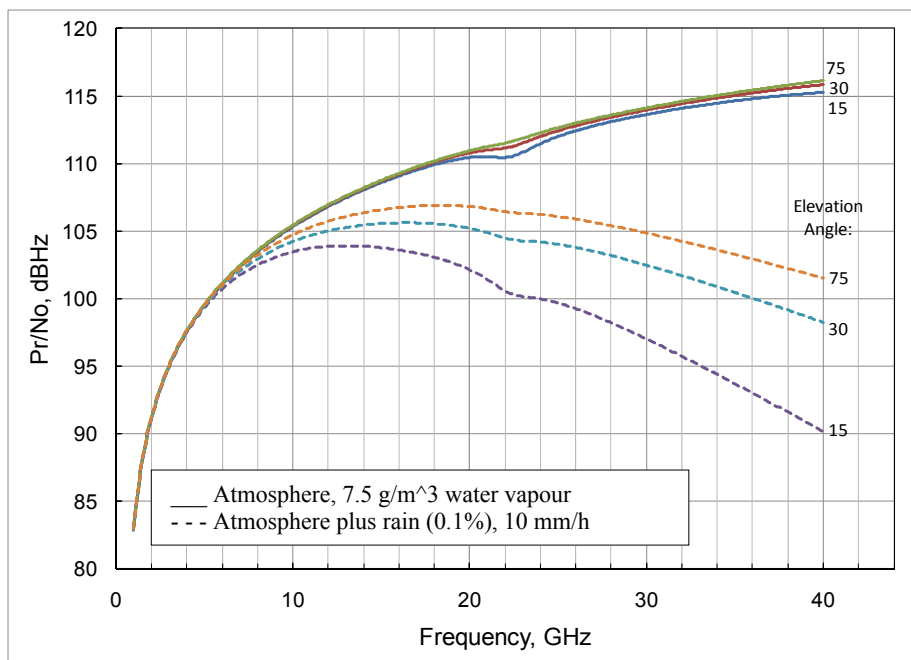


FIGURE 3b)

Achievable Earth-to-space link performance as limited by natural propagation phenomena and equipment characteristics
 (earth station antenna = 70 m, space station antenna = 3.7 m)

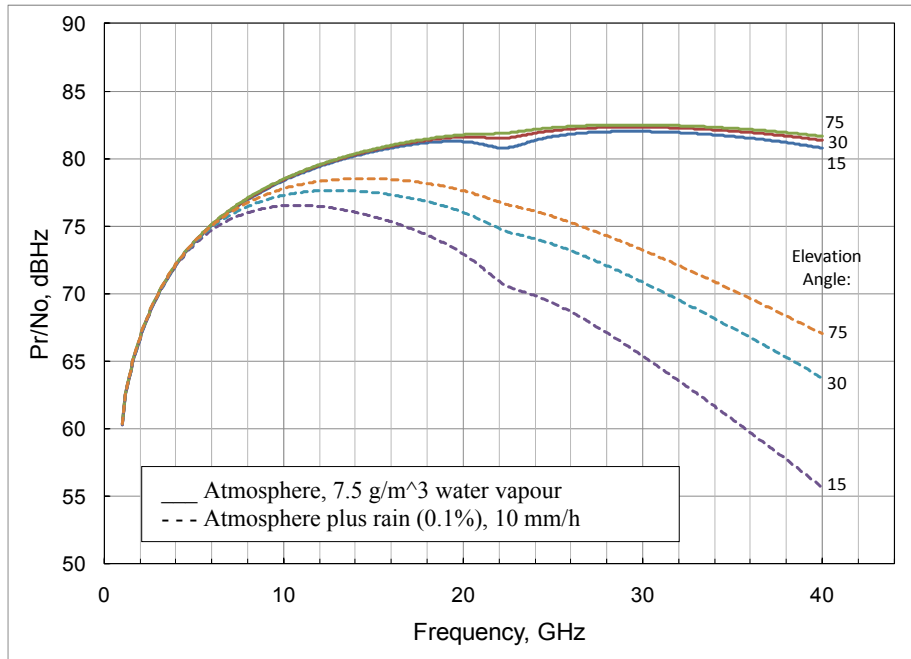


FIGURE 4a)

Ideal Earth-to-space link performance as limited only by natural propagation phenomena
 (earth station antenna = 70 m, space station antenna = 0 dB (fixed gain))

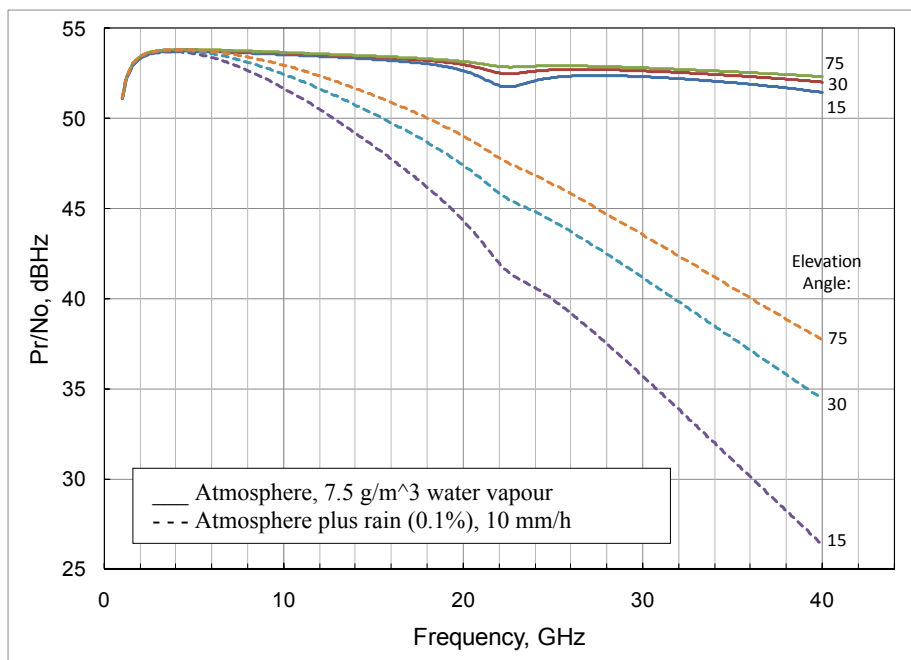
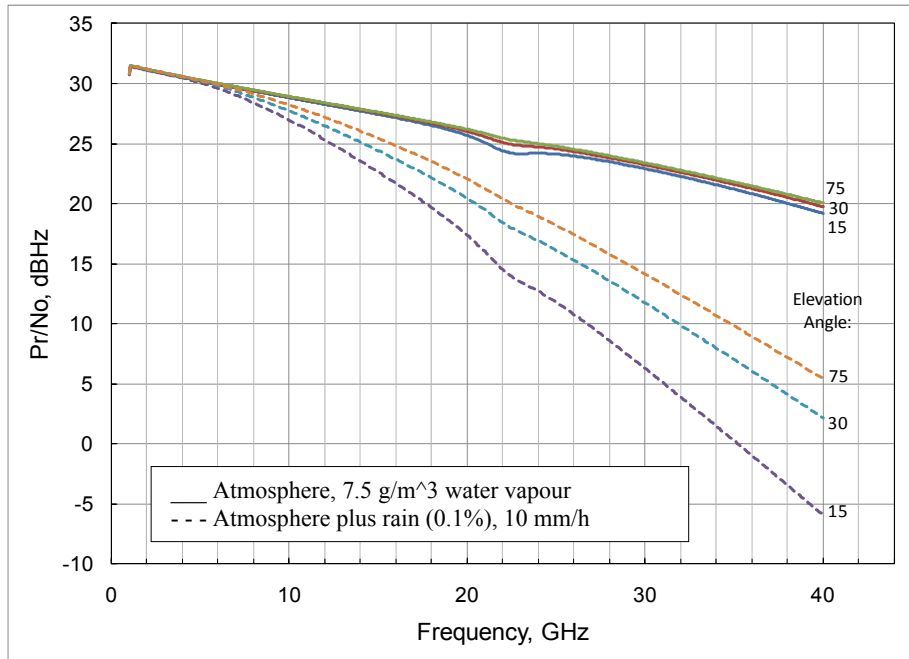


FIGURE 4b)

Achievable Earth-to-space link performance as limited by natural propagation phenomena and equipment characteristics
(earth station antenna = 70 m, space station antenna = 0 dB (fixed gain))



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

TABLE 1

Preferred frequency bands: space-to-Earth

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

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

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

TABLE 2

Preferred frequency bands: Earth-to-space

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

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

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

2.4 Preferred frequency bands in the 1-40 GHz range

Table 3 lists preferred frequency bands in the 1-40 GHz range as determined by link performance analysis and additional considerations of diplexer characteristics and bandwidth requirements.

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

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

Preferred frequency bands in the 1-40 GHz range and their application^(*)

Frequency band (GHz)	Direction	Spacecraft antenna	Weather Condition
1-2	Earth-to-space	Wide-beam low-gain	Clear or rain
1-4	Space-to-Earth	Wide-beam low-gain	Rain
1-6.5	Space-to-Earth	Wide-beam low-gain	Clear
3.5-9	Space-to-Earth	High-gain	Rain
6-16	Earth-to-space	High-gain	Rain
11.5-35.5	Earth-to-space	High-gain	Clear
26-40	Space-to-Earth	High-gain	Clear

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

2.5 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 to return back to the 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 μ s 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:

$$N = 10^{12} \left[\frac{221}{r^6} + \frac{1.55}{r^{2.3}} \right] \quad (1)$$

where:

- N : electron density (electrons/m³)
- 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:

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

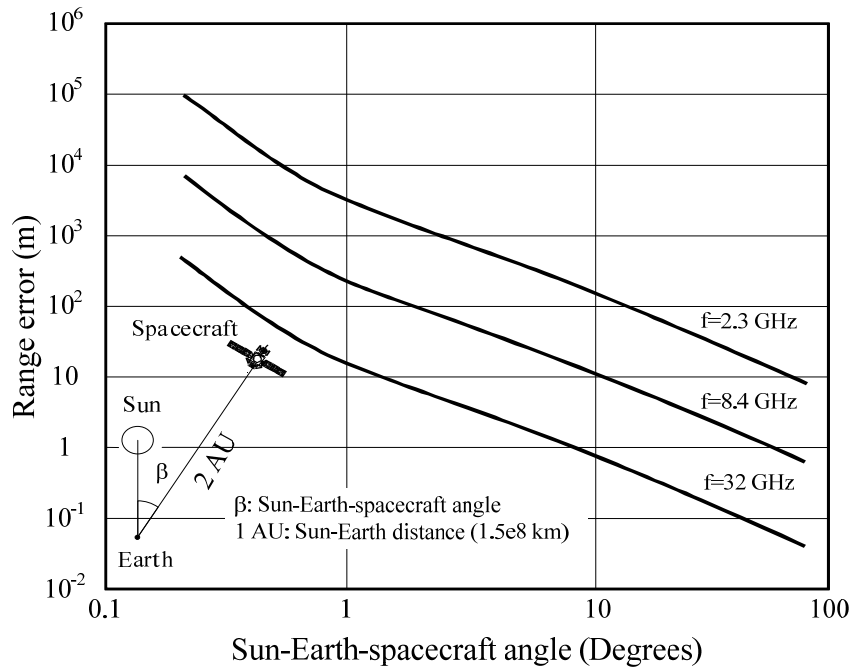
where:

- t : group delay caused by charged particles (s)
- f : frequency (Hz)
- N_s : total electrons/m² 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 uncorrelated group delay



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.

3 Selection of frequency bands in the 40-120 GHz range

The performance of links between earth stations and stations in deep space is affected by the atmosphere of the Earth. Attenuation and emission by the atmosphere generally limits deep-space telecommunications. There are, however, certain frequency bands where atmospheric attenuation is low enough to permit links between earth stations and deep-space stations. Additionally, there are certain bands that would be particularly suitable for links between an earth-orbiting relay station and deep-space stations.

3.1 Advantages of higher frequencies

Radio frequencies above 40 GHz can provide advantages for deep-space telecommunications. The advantages are higher link performance, potential for wider bandwidth, reduced errors in measurements that depend on the velocity of propagation, and the possibility of shielding from terrestrial interference.

3.1.1 Increased link performance

For a fixed transmitter power, the power received via a free-space link between perfect antennas with fixed apertures varies in direct proportion to the frequency squared. A practical example of this circumstance is the case of a path between a spacecraft in deep space and a relay satellite in orbit above the atmosphere of the Earth. If technology does not limit the choice of frequency in a particular range that is being considered, the highest frequency in that range will provide the best link performance.

For transmission through the atmosphere, there are certain bands above 40 GHz where the atmospheric attenuation is low enough to allow practical communication.

The increased performance of higher frequency links may be utilized for command, telemetering and radiometric functions. Alternatively, the higher performance may be traded for smaller and lighter spacecraft antennas and transmitters.

3.1.2 Wider bandwidth

At higher frequencies, it is usually possible to provide wider band allocations. Such allocations can accommodate wider transmission bandwidths. The wider bandwidth permits use of more complex coding schemes which provide reduced data error rates and reduced susceptibility to interference.

3.1.3 More accurate measurement of phase and group-delay

Accurate navigation of deep-space probes depends, in part, upon determination of their position and velocity by means of phase and group-delay measurements of received signals. These measurements are influenced by the velocity of propagation along the transmission path as shown in § 2.5. The velocity of propagation is a function of the density of charged particles along the path. The effect of these particles varies inversely with the square of the frequency and, hence, higher frequencies are preferable for purposes of navigation and certain other radio measurements.

3.1.4 Shielding from terrestrial interference

It may be desirable to employ a geostationary relay station for signals to and from deep-space probes. The links between such a station and deep-space probes would be free of the perturbing effects of the atmosphere. These links could also be protected from terrestrial interference by choosing frequencies where the atmosphere is relatively opaque to radio signals. There are such frequencies in the 40-120 GHz range.

3.2 Basis for frequency selection

Selection of preferred frequencies is based on link performance as affected by propagation and equipment characteristics. In the next sections of this Report, we examine the factors that influence frequency selection. Some of these factors provide the information needed to calculate an index of link performance. This index may be expressed as P_r/N_0 , the ratio of total received power to noise power spectral density for a particular set of propagation conditions and equipment parameters.

3.3 Frequency-dependent characteristics of interplanetary propagation

Interplanetary propagation attenuation, sky noise temperature, velocity of propagation and scintillation determine the performance of links between a deep-space probe and a relay satellite located outside the atmosphere of the Earth. These characteristics also affect the performance of links between earth stations and deep space.

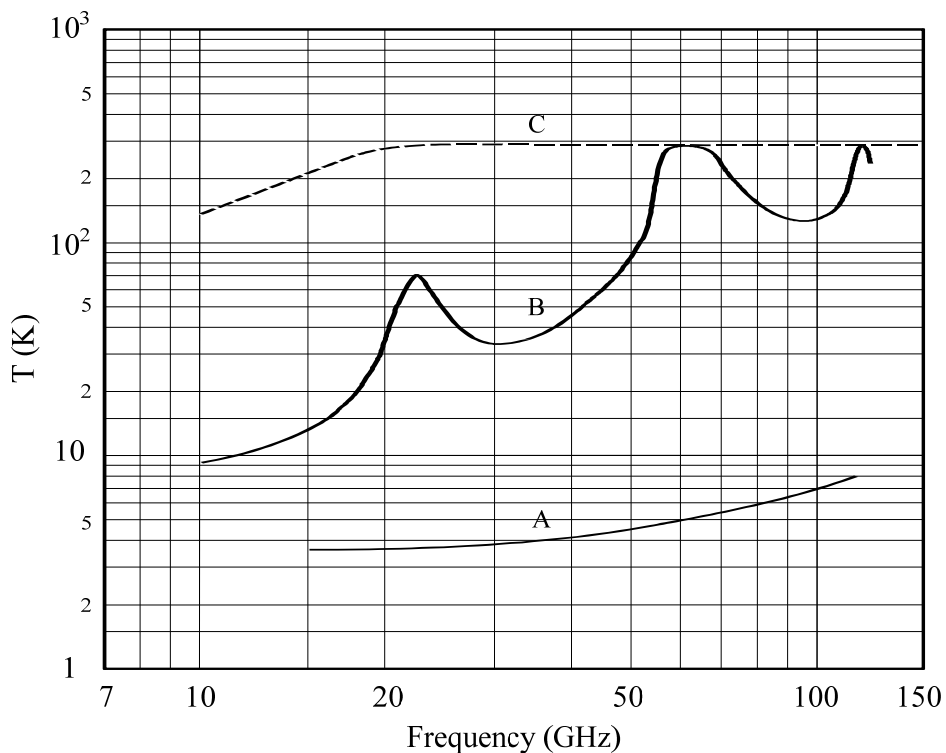
3.3.1 Interplanetary attenuation

Outside of planetary atmospheres, gaseous absorption or scattering by dust, the interplanetary medium will attenuate a signal by less than 0.1 dB in the 40-120 GHz range, as long as the propagation path is restricted to our solar system. Attenuation by interplanetary space may, therefore, be considered a negligibly small factor in the selection of preferred bands.

3.3.2 Interplanetary sky noise temperature

The sky noise temperature seen by a relay satellite will be determined by the cosmic background (3 K) and quantum noise as shown in curve A of Fig. 6, except when noise from the Earth, the other planets, or the Sun enters the antenna. The effect of these noise sources is discussed in Recommendation ITU-R P.372.

FIGURE 6
Sky noise temperature



Curves:

- (A) Gaseous atmosphere (as seen by deep space station)
- (B) Gaseous atmosphere (as seen by an Earth station, antenna at 30 degree elevation angle)
- (C) Composite of gaseous atmosphere plus rain exceeded 0.001% of time (55 mm/h rain climate J) (as seen by Earth station at 30 degree elevation angle)

The sky noise temperature seen by a spacecraft will be higher than that shown in curve A because the Earth will generally be within the main lobe of a spacecraft antenna pointed at a relay satellite. The black-body temperature of the Earth will contribute to the receiving system noise temperature. For example, for a spacecraft at 4×10^7 km from the Earth (the minimum distance to Venus), the Earth subtends an angle of 0.018° . If the spacecraft antenna is limited to a minimum beamwidth of 0.15° by pointing accuracy, then the Earth can fill less than 1.5% of the antenna main lobe. The effect of the black-body temperature of the Earth is to double (approximately) the effective sky

noise temperature. This temperature is small as compared to the 600-1 500 K noise temperature of a typical spacecraft receiving system. (In the 40-120 GHz range the black-body temperature varies between 210 and 290 K, depending on frequency and sub-spacecraft longitude on the Earth.)

A relay satellite may employ a receiver with a noise temperature substantially less than 600 K, but this would not strongly influence the selection of preferred frequency bands in the range being considered.

In this frequency range, the noise temperature seen by an antenna pointed in the direction of the Sun is 6 000 K. This very large increase in the system noise temperature must usually be avoided and can, therefore, affect the timing and design of some deep-space missions and experiments.

3.3.3 Sky noise temperature at earth stations

Sky noise temperature as seen by an earth station is a function of frequency, elevation angle, and atmospheric conditions (Recommendation ITU-R P.372). Curves B and C in Fig. 6 are representative of sky noise temperature during clear weather and during heavy rainfall.

When the earth station antenna is pointed near the Sun, the noise temperature will increase.

3.3.4 Velocity of interplanetary propagation

Charged particles along the communication path cause changes in the velocity of propagation. Figure 5 in § 2.5 shows an example of the range measurement error as a function of frequency and the angle between the ray path and a line between the earth station and the surface of the Sun. Although the curves in the figure do not include frequencies above 32 GHz, the trend to still lower errors continues as frequencies rise to higher values. It is apparent that high frequencies are desirable for the most precise ranging.

3.3.5 Interplanetary scintillation

Amplitude and phase scintillation from solar plasma can reduce link performance for ray paths close to the Sun. The magnitude of the scintillation decreases with increase in frequency.

3.4 Frequency-dependent characteristics of propagation through an atmosphere

The foregoing interplanetary propagation factors affect links between deep space and a geostationary relay station. For links between deep space and the Earth, the atmosphere plays a dominant role in the selection of preferred frequencies in the 40-120 GHz range.

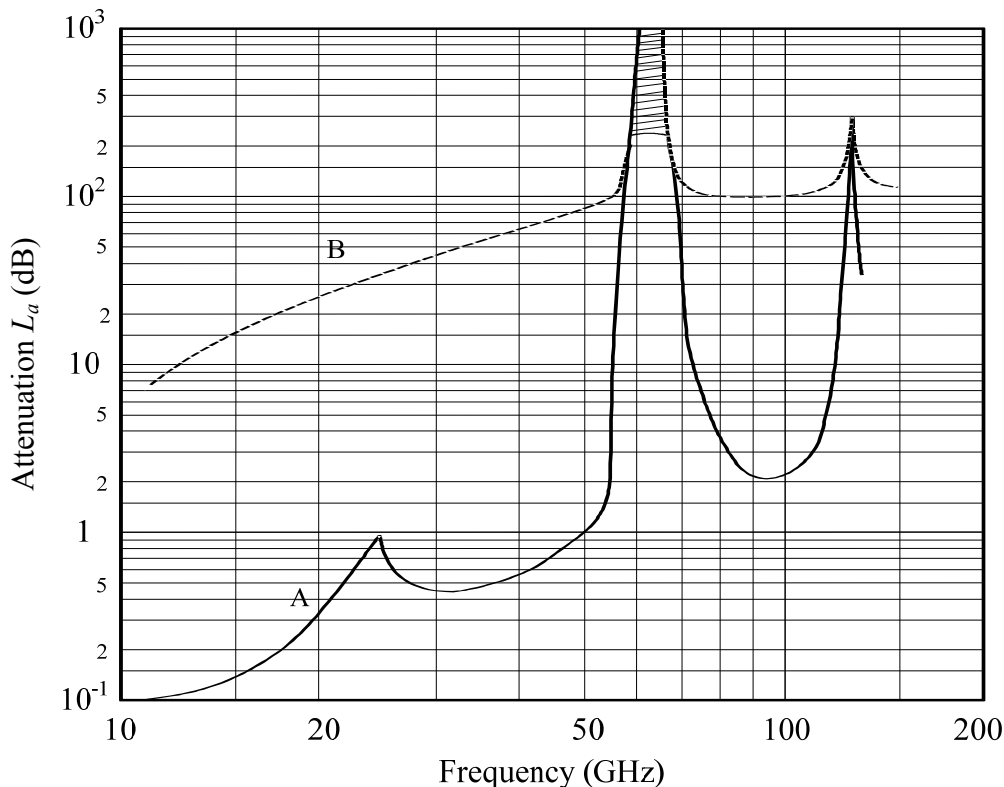
Planetary atmospheres can affect paths that graze or penetrate them.

3.4.1 Atmospheric attenuation

Attenuation of signals passing through the ionosphere of the Earth is negligible at frequencies above 40 GHz, but the neutral atmosphere plays a major role at these frequencies. The attenuation for transmission through the atmosphere is shown in Fig. 7 (Recommendation ITU-R P.676). Above 40 GHz, minimum attenuation on links between the Earth and spacecraft would be obtained at frequencies near 90 GHz.

FIGURE 7

Attenuation due to the gaseous atmosphere and rain for an antenna elevation angle of 30° at an earth station



Curves:

- (A) Gaseous atmosphere (7.5 g/m³ water vapor at surface)
- (B) Composite of gaseous atmosphere plus rain exceeded 0.001% of time (55 mm/h rain climate J)

The specific attenuation due to rain at rates greater than a few mm/h is larger than that of the gaseous atmosphere and increases monotonically with frequency in the range of interest. The rain rate for 0.01% of the time in a median rain climate is greater than 30 mm/h (see Recommendation ITU-R P.837). The attenuation in the 40-120 GHz region during rain at this rate is so high (Recommendation ITU-R P.838) that telecommunication between the Earth and spacecraft in deep space is generally not practicable and will not be considered further as a determinant of preferred frequencies.

For relay satellite-to-spacecraft links, the line-of-sight propagation paths will be obscured at times by the interposition of the Earth or some portion of the Earth's atmosphere. From a geostationary satellite, the solid Earth (not including the atmosphere) subtends a planar angle of 17.34°. If the atmosphere from the surface of the Earth up to an altitude of 100 km were opaque to radio waves the obscuration angle would increase by 0.27°. The effect of atmospheric attenuation on the obscuration angle is so small that this factor does not influence the selection of preferred frequency bands.

The objective of protecting the paths between deep-space probes and an Earth satellite from terrestrial interference may be satisfied by taking advantage of the high atmospheric attenuation in the 60 and 119 GHz regions (Recommendation ITU-R P.838). Molecular oxygen absorption lines at these frequencies are responsible for the high attenuation observed in Fig. 7.

From the standpoint of attenuation, the nature of the atmospheres of other planets does not influence the selection of communication frequencies in the 40-120 GHz range. This is not to say that the atmospheres of some planets do not contain spectral lines of scientific interest in this frequency range, for example, ammonia.

3.4.2 Atmospheric scintillation

Amplitude and phase scintillation from the neutral atmosphere is discussed in Recommendation ITU-R P.618. The effects increase with frequency for a fixed antenna aperture and at 100 GHz may cause signal amplitude fluctuations between 0.4 dB and 3.8 dB for a 3.7 m parabolic dish antenna.

Scintillation due to the Earth's ionosphere will not be a selection factor for frequencies above 40 GHz (Recommendation ITU-R P.531), and the same conclusion can be drawn relative to planetary ionospheres. For some missions, scintillation caused by the solar corona could affect the choice of frequency.

3.5 Frequency-dependent equipment factors

Equipment characteristics which determine link performance include transmitter power, antenna size, surface accuracy, pointing accuracy, and receiver noise temperature. These characteristics usually depend upon frequency to some degree. In the frequency range 40-120 GHz, for paths between the Earth and deep space, the effect of the atmosphere on link performance is so strong that the frequency-dependent equipment factors have only a minor effect on the selection of preferred frequencies.

Because of practical limits of wave polarizers and diplexers, simultaneous transmission and reception with a single antenna requires that the uplink frequency be separated by approximately 8 to 20% with respect to the downlink frequency. Pairs of bands chosen from the ranges listed in Table 4 must take this into account.

TABLE 4
Preferred frequency bands in the 40-120 GHz range and their uses

Range of preferred frequencies (GHz)	Application	Other requirements ⁽¹⁾
56-64	Relay satellite to deep space, and deep space to relay satellite, shielded from terrestrial signals	A pair of 1 000 MHz wide bands within the range, spaced by 8-20%
80-100	Deep space-to-Earth, and Earth-to-deep space	A pair of 1 000 MHz wide bands within the range, spaced by 8-20%
98-110	Relay satellite to deep space (for use in connection with a link in the 117.7-119.8 GHz band)	1 000 MHz wide band spaced 8-20% from the band in the 117.7-119.8 GHz range
117.7-119.8	Deep space to relay satellite, shielded from terrestrial signals	1 000 MHz wide band

⁽¹⁾ The spacing percentage applies to a pair of frequencies, one in each of the two bands, and not to the width of each band. For example, if the lower edge of one band is at 56 GHz, the lower edge of the other band must be in the range between 1.08 and 1.2 times 56 GHz.

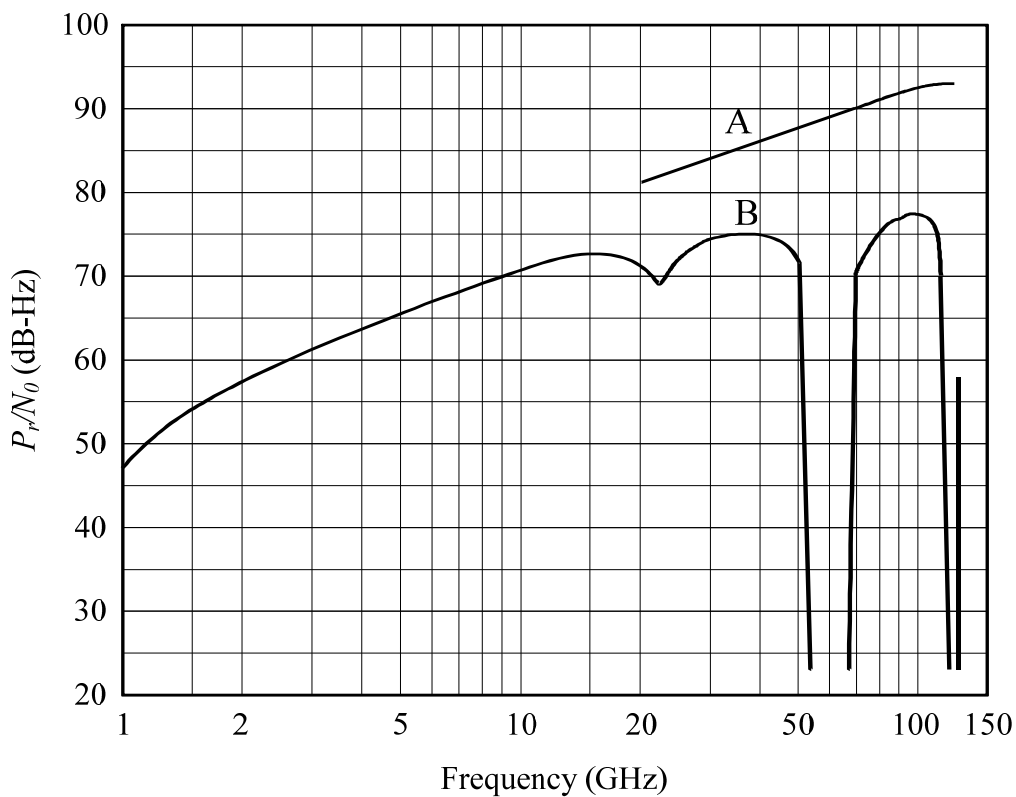
3.6 Example of link performance analysis

Figure 8 illustrates link performance as a function of frequency. Curve A is for a path in free space. Curve B includes the effect of the atmosphere of the Earth. The index of performance P_r/N_0 (see § 3.2) was calculated on the basis of data in Figs 6 and 7 and the following parameter values:

- Communication distance: 8×10^8 km
- Spacecraft transmitter power: 25 W
- Diameter of spacecraft antenna: 3.7 m
- Diameter of earth station antenna: 64 m

FIGURE 8

Link performance limited only by natural propagation phenomena for two fixed diameter antennas:
3.7-m deep-space station antenna, 64-m receiving station antenna



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

The antennas are assumed to be ideal with gain that is proportional to frequency squared.

These values are illustrative only; other values could be used. Different numerical results would be obtained, but the shape of the performance curves and the corresponding frequency selection would not change.

Comparison of Curves A and B shows the advantage in link performance that results from utilizing higher frequencies when the path is entirely in space. This is a principal reason for establishing a relay station in an earth satellite.

Curve B shows that frequency bands within the 40-120 GHz range can provide for transmission through the atmosphere, and for shielding of paths between a relay satellite and deep-space probes for terrestrial signals.

3.7 Preferred frequency bands in the 40-120 GHz range

The preferred frequency bands for deep space in the 40-120 GHz range are listed in Table 4. The bands were selected on the basis of:

- the attenuation and noise temperature characteristics of propagation through the atmosphere;
- the requirement to provide links between a relay satellite and a station in deep space that are shielded from terrestrial signals;
- the requirement for links that permit communication between a deep-space station and either a relay satellite or an earth station.

The feasibility of band sharing, and existing allocations in the Radio Regulations, were not factors in the selection of bands. The frequency-dependent characteristics of scintillation and velocity of propagation were not used as determinants of preferred frequency bands. These factors could influence the use of certain allocated bands for particular space research missions, but communication performance was considered the dominant factor in preferred band selection. Similarly, equipment characteristics that vary with frequency were not used to influence band selection. Bands that may be allocated will likely remain for many years, and equipment technology will develop to make best use of those frequencies, as limited by natural propagation phenomena.

A pair of links (probe-to-Earth satellite and vice versa) could be accommodated in the high attenuation range between 56 and 64 GHz. A frequency separation of approximately 8-20% is required. The absorption line at 119 GHz is much narrower, and because of the requirement for frequency separation of 8-20%, only one link of a pair could benefit from the maximum shielding. In this case, shielding of the link from the spacecraft to the relay satellite is most important.

4 Conclusions

This Report presented several factors for selecting frequency bands in the 1-120 GHz range that are preferred to be used by the deep space research. The factors considered include equipment characteristics, transmit and receive antenna sizes and gains, transmit powers, receiver noise temperatures, atmospheric propagation losses, and interplanetary propagation losses. The preferred frequency bands in the 1-40 GHz range and in the 40-120 GHz range are given by Table 3 and by Table 4, respectively.

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