CCIR Papers on Telecommunications for Deep Space Research

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Three JPL papers on telecommunications for deep space research have been adopted by Study Group 2 of the International Radio Consultative Committee (CCIR). In this article we present the paper that deals with the selection of preferred frequency bands in the 1-20 GHz range. Topics include propagation factors, equipment considerations, and communication link performance.

Study Group 2 of the International Radio Consultative Committee (CCIR) is concerned with the technical aspects of telecommunications for space research and radio astronomy. Three JPL papers on deep space research were submitted by the United States for consideration at a meeting held in Geneva during September, 1977. The papers were adopted and are:

Doc. 2/296 Telecommunication Requirements for Manned and Unmanned Deep Space Research

Doc. 2/269 Preferred Frequency Bands for Deep Space Research Using Manned and Unmanned Spacecraft

Doc. 2/279 Protection Criteria and Sharing Considerations Relating to Deep Space Research

The first of these papers was included in the September-October issue of the *Deep Space Network Progress Report* (PR 42-42). Also in that report was a description of the role of CCIR papers in the establishment of worldwide regulations that determine the use of the radio frequency spectrum.

In this article the second paper is presented. It considers the selection of frequencies most appropriate for meeting the telecommunication requirements of deep space research.

The third paper considers interference protection and band sharing with other users. This paper will appear in a future issue of the *DSN Progress Report*.

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WORKING GROUP 2-B

Draft New REPORT*
PREFERRED FREQUENCY BANDS FOR DEEP SPACE RESEARCH USING MANNED AND UNMANNED SPACECRAFT
(Study Programme AQ/2)

1. Introduction

Mission requirements, equipment factors and link performance define the frequency bands that are preferred for deep space research using manned and unmanned spacecraft. This report presents the preferred bands and selection considerations. Doc. 2/296 contains a detailed discussion of the telecommunications requirements for deep space research that were used in determining the preferred frequency bands.

2. Mission requirements

2.1 Telecommand and maintenance telemetering

Mission safety and success require that telecommand and maintenance telemetering be accomplished regardless of weather conditions. These functions must be possible during planned and unplanned space station attitudes that preclude use of the space station high gain primary antenna. Where link performance permits, a low gain secondary antenna may be carried for use in such cases. This antenna is nearly isotropic and must be considered when selecting operating frequencies.

2.2 Science telemetering

Selection of the best frequency for mission science telemetering includes consideration of the risk of degraded link performance caused by weather conditions. For some missions, unique data must be sent at a particular time, and reliable telemetering during adverse weather conditions is a necessity. For missions where unique data can be stored for most effective playback to Earth, a frequency may be selected for maximum data rate during clear weather. The maximum data rate objective can also be satisfied for those missions where data timing is not important or when particular data may be repeatedly acquired, as in some planetary orbiter missions.

2.3 Doppler and range tracking

Doppler and range tracking must be accomplished with an exactitude that satisfies mission navigation and radio science requirements. These determine the needed ranging accuracy and the necessary precision in the measurement of the effects of charged particles.

Charged particle calibration can be done with paired Earth-to-space and space-to-Earth frequencies in a single band. Increasing tracking accuracy requirements will necessitate calibration using two or more frequency pairs in different bands.

2.4 RF carrier tracking

For missions where it is required to maintain communication as the ray path passes close to the Sun, frequency selection must consider the scintillation effects of transmission through the solar plasma. These cause broadening of the RF carrier and difficulty in maintaining coherence in a narrow band phase-locked loop. No telemetering, Doppler measurements, or ranging can be conducted unless the carrier can be phase-locked.

*Proposed replacement for Draft Report AN/2, SG 2 Interim Meeting, Geneva, March 1976.

2.5 Bandwidth

Telemetering and telecommand data rates tend to rise with improving technology. Increased rates require wider bandwidth, particularly for coded transmission.

The need for increased ranging accuracy will require greater ranging bandwidths. In some cases, the ranging signal will determine the total bandwidth requirement, and frequency selection for this function may be constrained by the width of the allocated band.

Where simultaneous communication is conducted with several spacecraft within a single antenna beam, the total needed bandwidth is increased proportionally. A detailed discussion of bandwidth requirements will be found in Doc. 2/296.

3. Equipment factors

Earth stations include large steerable parabolic antennae, high power transmitters and sensitive receivers. All of these are very expensive and infrequently constructed. For this reason, analysis of link performance versus frequency considers the earth station antennae to be of fixed diameter.

Earth station equipment has been built and is operating in the 2 and 8 GHz allocations. The selection of frequency bands must consider the realities of existing equipment. There is more freedom of choice in higher frequency bands, since operational capability has yet to be developed above 10 GHz.

The link analyses presented in the Annex are based upon a fixed diameter earth station antenna, and both fixed diameter and fixed beamwidth space station antennae. The fixed diameter space station case arises when the largest possible antenna may be used, free of pointing limitations. The fixed beamwidth case is in effect when antenna pointing accuracy determines the minimum beamwidth, or when the antenna must give wide coverage to permit communication without regard to space station attitude.

Because of the practical limits of diplexers, Earth-to-space and space-to-Earth pairs of frequency bands must be separated by at least 7% to allow simultaneous transmit-receive operations with a single antenna.

Standard transponder designs currently used at 2 and 8 GHz employ specific receive/transmit frequency ratios that must be considered in determining preferred frequency bands.

4. Link performance

Maximum data rate capability is obtained by using bands appropriate for weather conditions and space station antenna limitations. Tables I and II show optimum link frequencies selected on the basis of the analysis in the Annex.

Optimum frequencies for clear weather will tend to increase as technology improves. For rain, the optimum space-to-Earth frequency will tend to decrease slightly because the sky noise caused by rain will dominate system performance.

Table I. Optimum frequency bands for space-to-Earth links

Space Station Antenna Limitation	Weather Condition	Best Performance Frequency Band (GHz)
Fixed diameter	Clear	10-14
Fixed diameter	Rain	4-6
Fixed beamwidth	Clear	1-2
Fixed beamwidth	Rain	1-2

Table II. Optimum frequency bands for Earth-to-space links

Space Station Antenna Limitation	Weather Condition	Best Performance Frequency Band (GHz)
Fixed diameter	Clear	12-20
Fixed diameter	Rain	7-9
Fixed beamwidth	Clear	1-2
Fixed beamwidth	Rain	1-2

5. Preferred frequencies

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 that will provide best performance. Best performance refers to error rate, measurement accuracy, data rate, link reliability or some combination of these parameters. The best performance that is obtainable at a particular time with a particular system depends upon propagation conditions. The objective of identifying preferred frequencies is to provide the basis for allocations from which the designer can select operating frequencies best suited to mission requirements.

Table III lists the preferred frequency bands and associated characteristics that would provide the needed range of choices for the conduct of deep space research.

Table IV compares the preferred frequencies with current allocations for deep space research. Existing earth and space stations use current allocations, even though these are not always optimum. Allocations in the 10-20 GHz range are needed for future missions requiring optimum link performance for very high telemetering rates and wideband ranging.

6. Conclusion

To meet the needs of the deep space research service, at least three pairs of Earth-to-space and space-to-Earth bands are required. The preferred frequencies for these pairs are shown in Tables III and IV.

The existing 2110-2120 MHz and 2290-2300 MHz allocated pair meet the requirement for weather independent links using either high or low gain spacecraft antenna. The 10 MHz allocation width imposes a limit on telemetering data rate and ranging precision, especially when communicating with two or more spacecraft within the earth-station antenna beam.

The existing 7145-7235 MHz and 8400-8500 MHz allocated pair provides increased link performance using the spacecraft high gain antenna. The 8 GHz allocation is not optimum, but provides acceptable performance. The 100 MHz allocation width allows telemetering and ranging that is adequate for current and near-future missions. These bands in combination with the 2 GHz allocations provide for multi-frequency charged particle calibration.

A new pair of bands between 10 and 20 GHz will be needed for clear weather use by future missions. These bands should be approximately 500 MHz wide to permit advanced radio science experiments that require ranging to centimetre accuracy, very high telemetering rates, and simultaneous operation with several spacecraft. These bands will also provide reduced charged particle delays and scintillation and thus permit operations with ray paths passing close to the Sun. In combination with the 2, 7 and 8 GHz allocations, they will allow very accurate measurement of charged particle effects.

Table III. Preferred frequencies and their uses

Region of Preferred Frequency	Use	Other Requirements
1-2 GHz	All weather Earth-to-space and space-to-Earth links using either the spacecraft high-gain, or the widebeam low-gain antennae. Used for telemetering, telecommand, tracking, and as part of multifrequency charged-particle calibration.	Earth-to-space and space-to-Earth bands separated by at least 7%.
4-6 GHz	All weather space-to-Earth link using the spacecraft high-gain antenna. Used for telemetering, tracking, and as part of multifrequency charged-particle calibration.	Requires Earth-to-space band of equal width to support two way tracking. (See 7-9 GHz preferred frequency.)
7-9 GHz	All weather Earth-to-space link using the spacecraft high gain antenna. Used for telecommand, tracking, and as part of multifrequency charged-particle calibration.	Requires space-to-Earth band of equal width to support two-way tracking. (See 4-6 GHz preferred frequency.)
10-14 GHz	Clear weather space-to-Earth link using the spacecraft high gain antenna. Used for telemetering, tracking, and as part of multifrequency charged-particle calibration.	Requires similar Earth-to-space band of equal width to support two-way tracking. (See 12-20 GHz preferred frequency.)
12-20 GHz	Clear weather Earth-to-space link using the spacecraft high gain antenna. Used for telecommand, tracking, and as part of multifrequency charged-particle calibration.	Requires similar space-to-Earth band of equal width to support two-way tracking. (See 10-14 GHz preferred frequency.)

Table IV. Preferred frequencies and current allocations

Region of Preferred Frequency (GHz)	Current Allocation (GHz)
1-2 Earth-to-space	2.110-2.120 Earth-to-space
1-2 Space-to-Earth	2.290-2.300 Space-to-Earth
7-9 Earth-to-space	7.145-7.235 Earth-to-space
4-6 Space-to-Earth	8.400-8.500 Space-to-Earth
12-20 Earth-to-space	None
10-14 Space-to-Earth	None

Frequencies near 30 GHz, and perhaps higher, will also be needed in the future for space-to-space communication.

ANNEX

FREQUENCY SELECTION CONSIDERATIONS FOR DEEP SPACE RESEARCH

1. Introduction

This Annex presents an analysis that provides the basis for the selection of frequencies for communication between deep space research earth and space stations.

The Annex considers link performance as a function of frequency by establishing an index of performance, using propagation factors derived from Reports 233-3, 205-2, 564 (Rev. 76), 234-3 (Rev. 76) and 263-3, and the principal elements of equipment technology which affect performance. Sets of curves are provided to illustrate the relative performance under various weather and antenna elevation angle conditions.

2. Calculation of link performance as a function of frequency

Telecommunication link performance includes frequency dependent parameters related to propagation and equipment factors. One index of performance is the ratio of received power-to-noise spectral density:

$$P_R - N_o = P_T + G_T - L_P - L_A - L_{Ra} + G_R - KT_T \qquad \text{(dB)}$$

where

P_R	=	received power	(dBW)
N_o	=	noise spectral density	(dBW/Hz)
P_T	=	transmitter power	(dBW)
G_T	=	transmitting antenna gain	(dBi)
L_P	=	path loss between isotropic antennae	(dB)
L_A	=	transmission loss through the atmosphere including water vapour	(dB)
L_{Ra}	=	transmission loss through rain	(dB)
G_R	=	receiving antenna gain	(dBi)
K	=	1.38×10^{-23}	(Joule/K)
T_T	=	total noise temperature	(K)

$$T_T = T_A + T_{Ra} + T_G + T_R \qquad \text{(K)}$$

where

T_A	=	noise temperature related to L_A	(K)
T_{Ra}	=	noise temperature related to L_{Ra}	(K)

T_G = galactic background noise temperature, after transmission losses through the propagation media (K)

T_R = noise temperature of receiver (K)

For an Earth-to-space link the noise power contribution of earth atmosphere and rain may be neglected and:

$$T_T = T_G + T_R .$$

The optimum frequency for a link with particular antenna and weather requirements may be determined by calculating the index of performance as a function of frequency.

3. Propagation considerations

Communication system performance depends on propagation characteristics, and these are frequency dependent.

3.1 Absorption attenuation by atmospheric gases and precipitation

Radio transmission through a clear atmosphere is subject to attenuation and reradiation by molecular oxygen and water vapour. The attenuation is a function of radio frequency and the oxygen and water vapour content along the transmission path. This is discussed in detail in Report 234-3 (Rev. 76).

Rain attenuation is a function of the radio frequency, rainfall rate, rain drop size, and drop distribution within the rain volume. This is discussed in detail in Report 233-3.

Figure 1 presents curves of attenuation between space and Earth as a function of frequency and elevation of the earth station antenna. The figure was derived from data in Reports 205-2, 233-3 (Rev. 76), 563 and 564 (Rev. 76). The curves labeled "clear weather" were calculated for one way attenuation through a moderately humid atmosphere (7.5 gm/m^3 at the surface). The curves for rain are for a rate (32 mm/hr) exceeded 0.01% of an average year in rain climate 4, and include the attenuation of the atmosphere.

3.2 Sky noise temperature

The following factors contribute to sky noise: atmospheric gases (principally oxygen and water vapour), precipitation, and galactic noise and cosmic background. Sky noise temperature caused by atmospheric gases and precipitation is a function of temperature and the attenuation along the transmission path, and is thus related to frequency and antenna elevation angle as discussed in Report 234-3 (Rev. 76). Report 205-2 contains curves of galactic and cosmic background noise. The contribution of these sources to total sky noise is modified by the attenuation along the path.

Figure 2 presents curves of total sky-noise temperature for the weather conditions of Figure 1, plus the contributions of galactic and cosmic background noise, calculated according to the preceding considerations.

3.3 Tropospheric scintillation and refraction

Reports 234-3 (Rev. 76) and 564 (Rev. 76) indicate that the propagation effects caused by tropospheric scintillation and refraction may be negligible, if transmission frequencies are below 20 GHz and antenna elevation angles are greater than 3^o. These effects have not been included in the analysis of preferred frequencies.

3.4 Ionospheric scintillation

Electron-density irregularities in the ionosphere create refractive inhomogeneities that result in signal amplitude and phase variations. Fading of 3 to 4 dB at frequencies in the 4 and 8 GHz range has been observed. Current information is insufficient for including this factor in frequency selection. Scintillation effects in the ionosphere are discussed in Report 263-3 (Rev. 76).

3.5 Variations in propagation velocity caused by charged particles

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 ray path, and inversely proportional to the square of the frequency. The group delay has been shown to be [Trask and Efron, 1966]:

$$\Delta t = \frac{40.3}{cf^2} \int N ds \text{ seconds}$$

where

Δt = group delay in seconds

f = the frequency of signal transmission in Hz

N = electron density in electrons/metre^3

s = ray path length in metres

c = speed of light in free space in metres/second

The effect is not a constant. Velocity scintillation phenomena are also observed. These cause phase modulation and spectrum broadening of the signal traversing the ionized medium.

An estimate of the upper limit on the propagation delay through the ionosphere ranges from 0.25 µs at 1 GHz to 62 nS at 20 GHz. Further discussion will be found in Report 263-3.

The solar plasma in interplanetary space modifies radio wave propagation velocity in the same way as the ionosphere. Deep space tracking measurements have yielded delay measurements from several locations in the solar system. The resulting electron density profile which those measurements provided is the basis for an approximation formula

$$N = 10^{12}\left(\frac{70}{r^6} + \frac{0.6}{r^2}\right)$$

where

N = electron density in electrons/metre^3

r = distance from Sun surface in Sun radii

Propagation delay can result in range measurement error. Consider the case of a spacecraft at a distance of 1 AU (1.5×10^8 km). The difference between indicated and actual range depends upon charged particle density along the path from Earth to the spacecraft, and is shown in Figure 3 for three different radio frequencies, as a function of the angle between the Earth-Sun (surface) line and Earth-spacecraft line. The figure was obtained by calculating propagation delay and then multiplying by the speed of light.

Spacecraft tracking depends on very accurate knowledge of propagation velocity to determine range for use in orbital calculations and charged particle effects are therefore important factors in frequency selection.

4. Equipment considerations

Equipment parameters considered in link performance analysis include transmitter power, antenna gain, and receiving system noise temperature. For additional discussion of these parameters see Doc. 2/296.

4.1 Transmitter power

Space station transmitter power is limited primarily by the available spacecraft primary power so that the obtainable RF output power is approximately independent of frequency in the 1-20 GHz range. Earth station transmitter power in the same frequency range is limited primarily by development cost.

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

4.2 Antenna gain

Antenna gain is limited by size, surface precision and structural deformation. For space stations, antenna size is limited by space available in the launch vehicle, by the state of development of unfurlable structures, and by the pointing capability of the space station.

Link analysis in this Annex assumes that the gain of a space station fixed diameter antenna increases directly as the frequency squared, since the effect of imperfections is negligible in the frequency range being considered. For the fixed beamwidth case the gain is assumed to be independent of frequency.

The earth station antenna gain for 1977 implementation is considered to follow the curve in Figure 3 of Doc. 2/296.

4.3 Receiving equipment noise temperature

The space station receiving system noise temperature is dominated by the input preamplifier. Antenna feedline losses are relatively unimportant in their noise contribution.

At earth stations there is no important size, weight, or complexity limitation, and the most sensitive possible receiver is needed.

Link analysis in this Annex assumes that for 1977 implementation the noise temperatures are as shown in Figure 2, Doc. 2/296.

5. Link performance

The frequency dependence of link performance may be shown by the variation in the ratio of total received power to noise spectral density, P_R/N_O. Curves of P_R/N_O, shown in Figures 4 through 7, were calculated by using data in Figures 1 and 2, equipment characteristics described in Doc. 2/296, and the following assumptions:

Communication distance	8×10^8 km
Earth station antenna	64 m
Earth station transmitter	100 kW

Space station antenna	3.7 m
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 numerical values of P_R/N_o depend upon the assumed link parameters. Different assumptions about communication distance, antennae characteristics and transmitter power would not significantly change the shape of the curves.

Figures 4 through 7 show curves for clear and rainy weather, and for earth station antenna elevation angles of 15° (near horizon), 30° and 75°. Figures 4(a), 5(a), 6(a) and 7(a) reflect the implementation limitations typical of 1977 earth and deep space stations. Gravity induced structural distortions on large earth station antennae reduce gain to an extent dependent on elevation angle. This effect is included in the figures for 1977, and is the cause of the crossing of several curves.

Figures 4(b), 5(b), 6(b) and 7(b) assume the use of perfect antennae and noiseless receivers. These curves illustrate ultimate performance as limited by natural phenomena, and demonstrate the effect of advancing technology.

6. Discussion

The performance curves were developed for clear weather and heavy rainfall conditions. The rainfall rate used in the analysis is the amount that is exceeded 0.01% of the time in rain climate 4. This rate, 32 mm/hr, was chosen to allow frequency selection that will satisfy the requirement for reliable telecommunication under adverse conditions. In Annex II, Report 536 (Geneva, 1974), there are curves for the condition of clouds and 4 mm/hr rain. Comparison of shape and maxima of the curves shows that selection of preferred frequencies is not significantly altered by consideration of more moderate weather.

The curves for the future performance as limited only by natural phenomena, i.e., weather and cosmic noise, show the link performance that may be approached as equipment and techniques become more fully developed.

References

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Key Words

Deep space research
Frequency selection
Performance
Telecommunications
Propagation effects

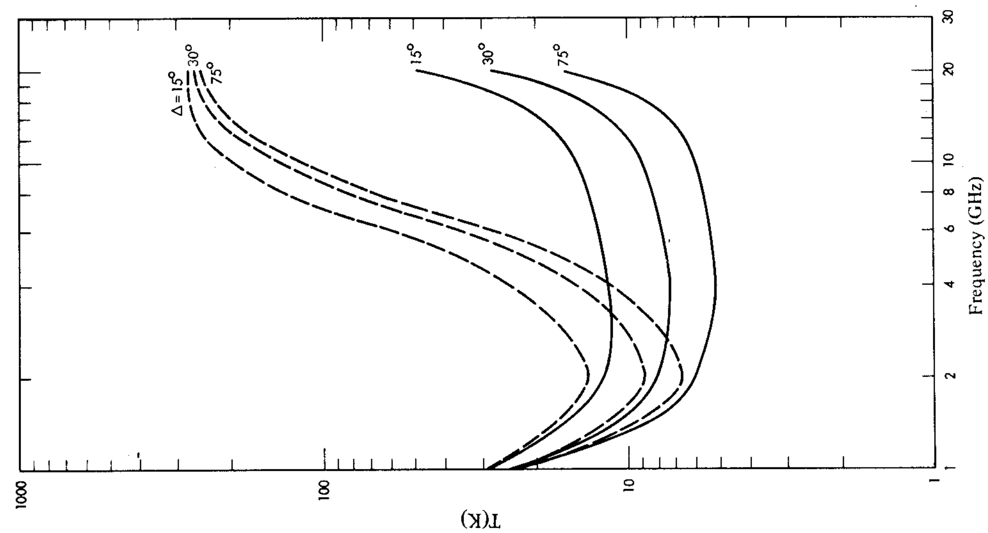


FIGURE 2

Sky noise temperature (T)

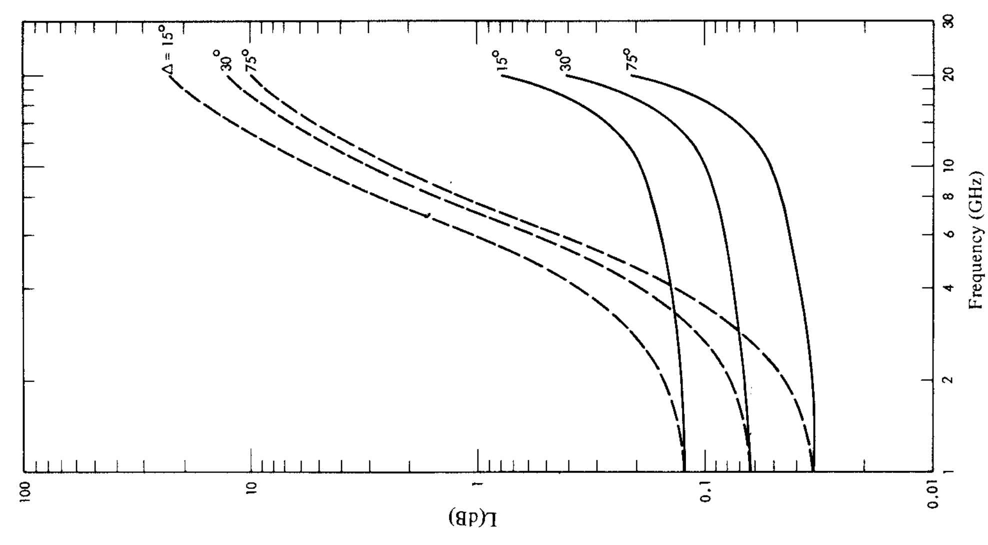


FIGURE 1

Attenuation (L) by atmosphere and rain

——— clear weather, atmosphere only

— — — rain and atmosphere

Δ: elevation of earth station antenna

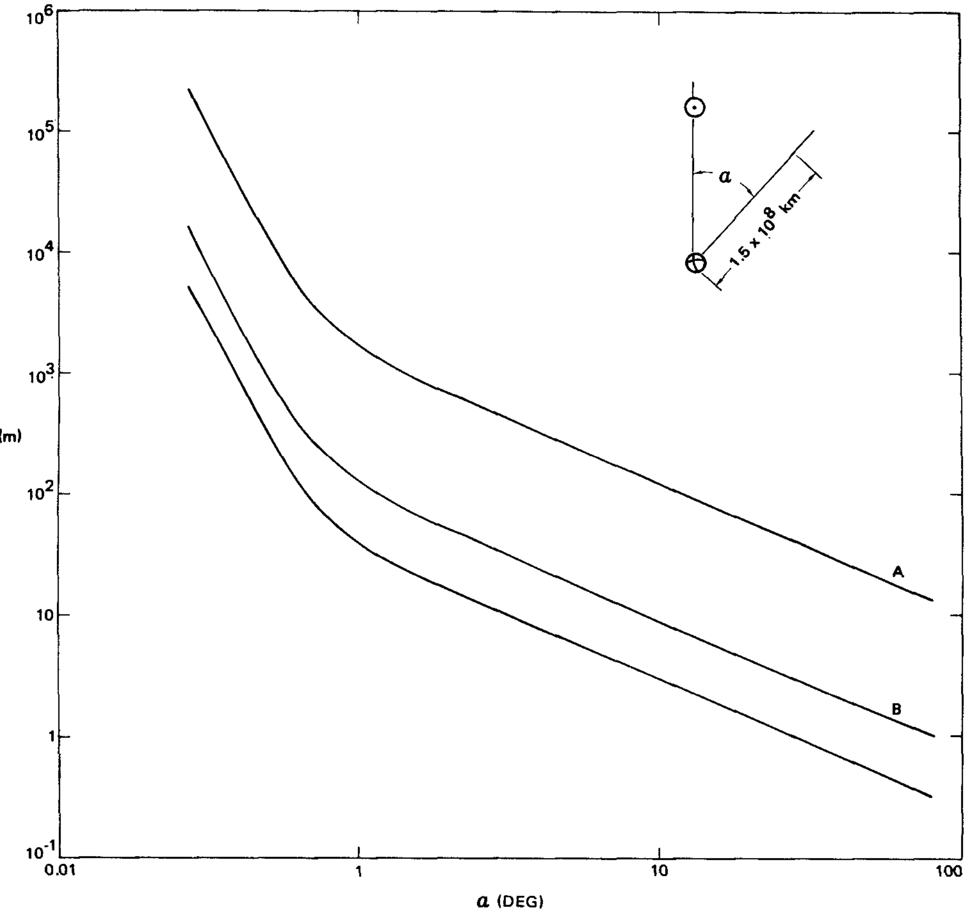
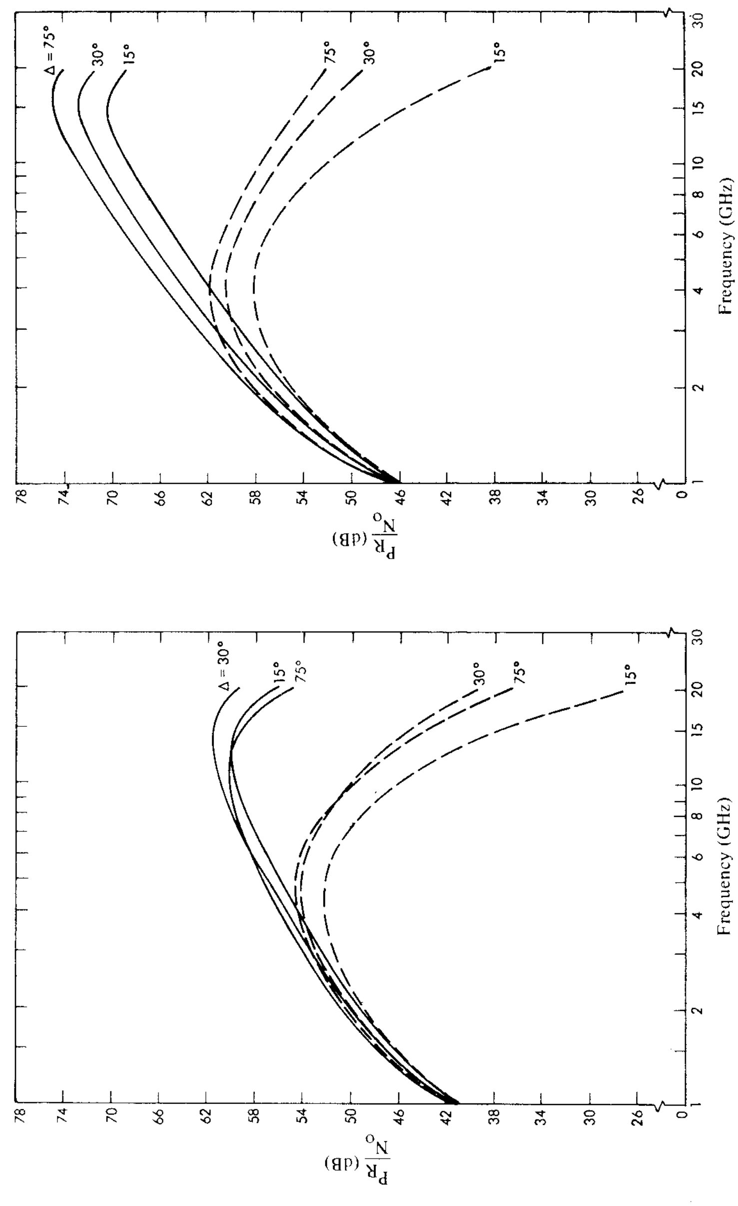


FIGURE 3.

Approximate error (ΔR) in measured spacecraft range caused by charged particles along a 1.5×10^8 km path, as a function of angle from center of sun (a)

A: 2.295 GHz
B: 8.450 GHz
C: 15.0 GHz

⊙ : SUN
⊕ : EARTH



(a) 1977 implementation

(b) Future limits from natural phenomena only

FIGURE 4

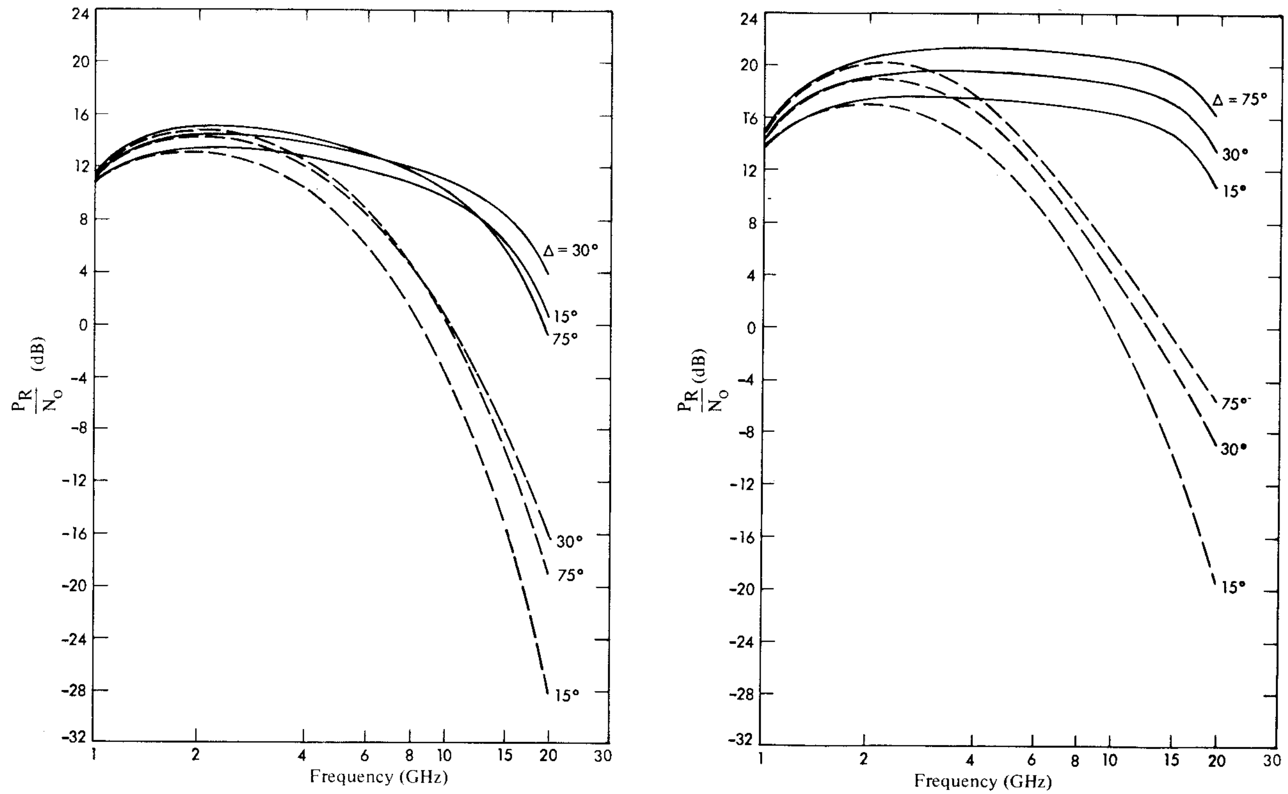
Space-to-earth link performance $\left(\frac{P_R}{N_o}\right)$

Two fixed diameter antennae

——— clear weather, atmosphere only

– – – rain and atmosphere

Δ : elevation angle of earth station antenna



(a) 1977 implementation

(b) Future limits from natural phenomena only

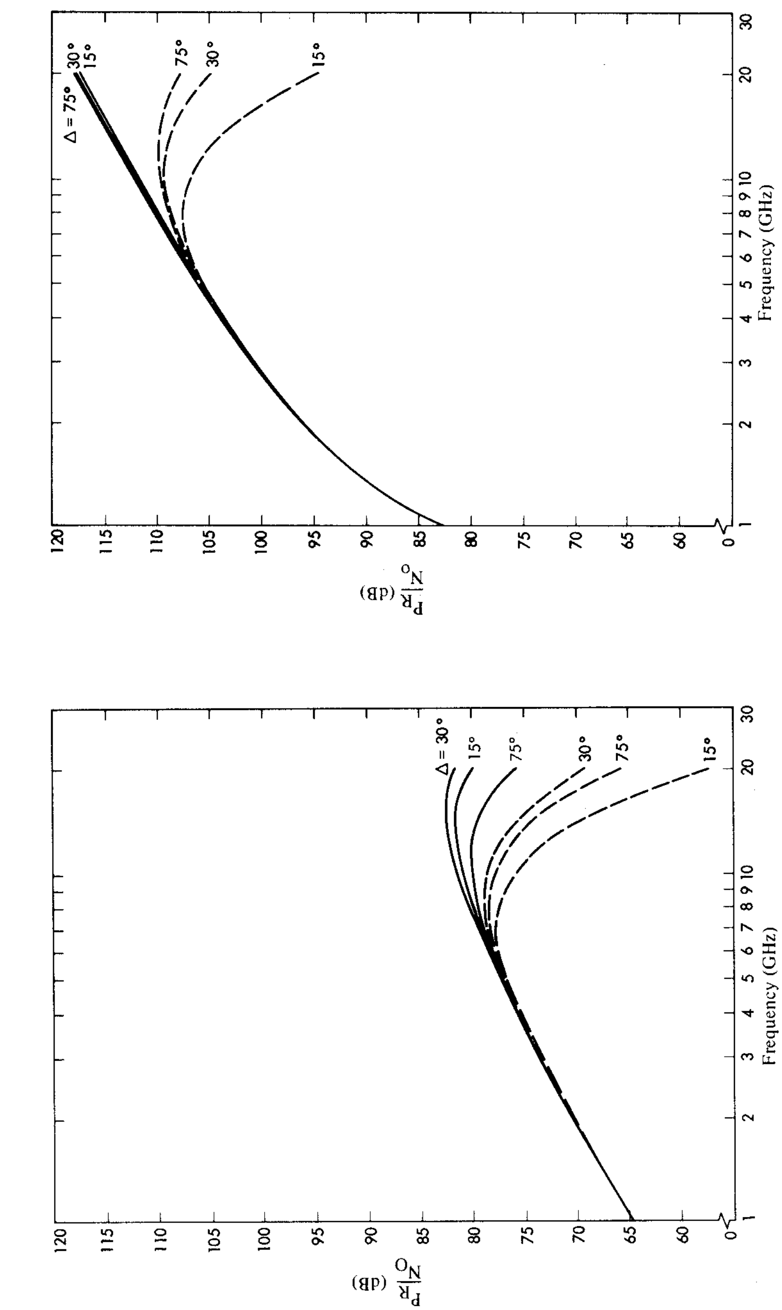
FIGURE 5

Space-to-earth link performance $\left(\frac{P_R}{N_o}\right)$

Fixed beamwidth space station antenna, fixed diameter earth station antenna

——— clear weather, atmosphere only
– – – – rain and atmosphere

Δ: elevation angle of earth station antenna



(a) 1977 implementation

(b) Future limits from natural phenomena only

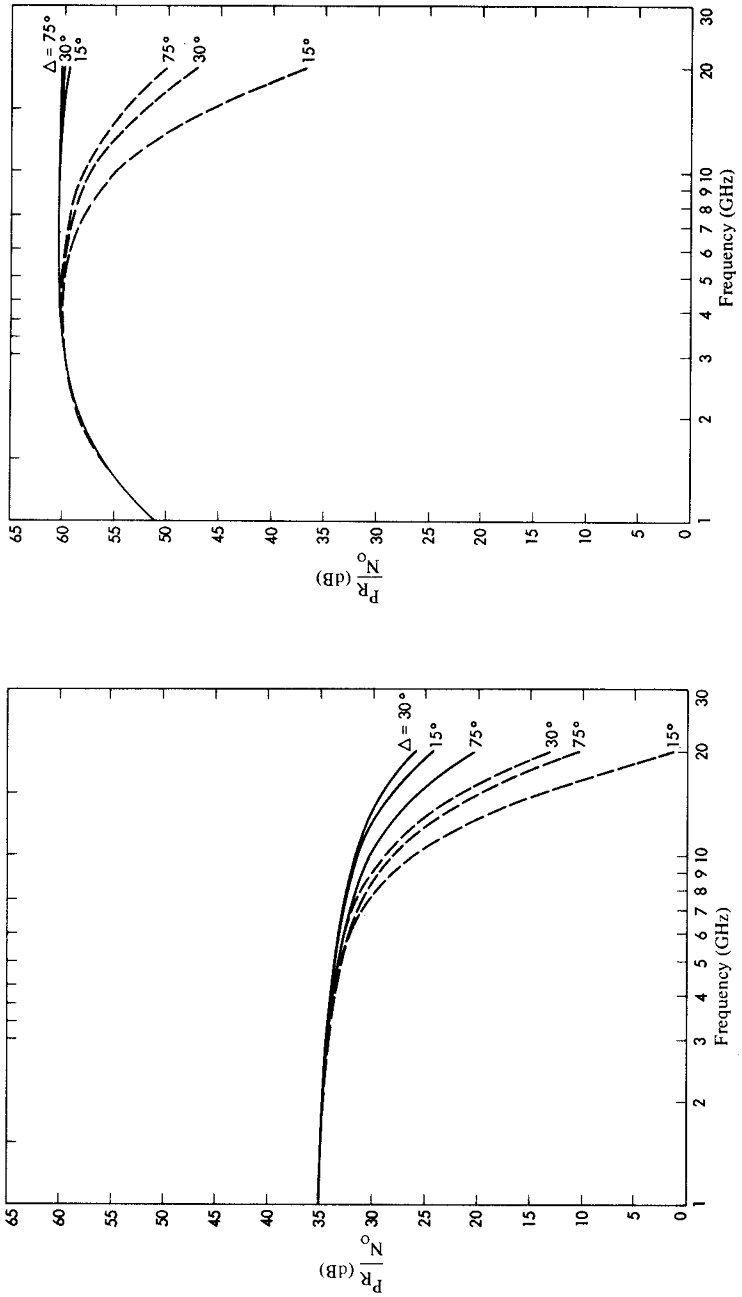
FIGURE 6

Earth-to-space link performance $\left(\frac{P_R}{N_o}\right)$

Two fixed diameter antennae

——— clear weather, atmosphere only
- - - - rain and atmosphere

Δ : elevation angle of earth station antenna



(a) 1977 implementation

(b) Future limits from natural phenomena only

FIGURE 7

Earth-to-space link performance $\left(\frac{P_R}{N_o}\right)$

Fixed diameter earth station antenna, fixed beamwidth space station antenna

——— clear weather, atmosphere only
– – – – rain and atmosphere

Δ : elevation angle of earth station antenna