CCIR Papers on Telecommunications for Deep Space Research

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Three JPL papers on telecommunications for deep space research were recently adopted by Study Group 2 of the International Radio Consultative Committee (CCIR). In this article, we present a brief description of United States participation in the process of developing the technical basis for international allocation and regulation of the radio frequency spectrum. The first of the three papers is then presented in its CCIR format and style. The paper considers the telecommunication requirements for deep space research. Topics include functional requirements, methods and techniques, and equipment characteristics.

In 1979 the United States will participate in a General World Administrative Radio Conference. The conference will be held in Geneva under the auspices of the International Telecommunications Union (ITU), a specialized agency of the United Nations. The purpose of the conference is to revise the international Radio Regulations that allocate and control the worldwide use of the radio frequency spectrum. The conclusions of the conference have treaty status and are subject to ratification by each participating nation. The last major revision of the Radio Regulations occurred in 1959.

Conference negotiations are based in large part on documents published by the International Radio Consultative Committee (CCIR), a part of ITU. A 13-volume set of reports and recommendations is revised and published by the CCIR at approximately four-year intervals. The several study groups of CCIR treat particular subjects such as propagation, broadcasting, mobile services, spectrum utilization, etc. Study Group 2 deals with space research and radio astronomy. The CCIR volumes are published after international discussion and approval, and thus provide an agreed-upon technical base for negotiating radio frequency allocations and regulations in consideration of social, economic and political factors.

To assist the U.S. Department of State in the preparation for the 1979 conference, NASA is participating in CCIR work in a number of technical areas. One of these is deep space research. The Spectrum Engineering Group of the Jet Propulsion Laboratory is conducting studies and writing CCIR documents in connection with the allocation and protection of radio frequency bands used for deep space research. These bands are shared with other services, within the United States and throughout the world.

An objective of the radio regulations is the protection of radio services from harmful interference. To continue and enhance the protection of deep space research telecommunications, a rationale for band allocation must be developed and agreed upon by 150 nations in a one-country, one-vote environment.

Three reports on deep space telecommunications, prepared within the Spectrum Engineering Group, were presented by the United States to the CCIR Study Group 2 Final Meeting held in Geneva during September 1977.

In Geneva, these reports were assigned to a working group with representatives from 7 countries. After minor revision by the working group, the papers were recommended to the full Study Group 2 for approval. The reports were approved, and next will be presented to the CCIR Plenary Assembly. Upon adoption by that body in mid-1978, they will be published as part of CCIR Volume 2, Space Research and Radio Astronomy.

The three deep space papers are:

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

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

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

The first of these papers is presented in this issue of the Deep Space Network Progress Report. The other papers will appear in future issues. Each paper will be reproduced in its original form to give to the reader a sense of the style and format of CCIR documents.

Documents
C.C.I.R. Study Groups
Period 1974 - 1978

Doc 2/296-E
26 September 1977

Original: English

WORKING GROUP 2-B

Draft New REPORT*
TELECOMMUNICATION REQUIREMENTS FOR MANNED AND UNMANNED DEEP SPACE RESEARCH
(Question (AZ/2))

1. Introduction

This report presents the characteristics of typical United States of America (U.S.) deep space research missions, the functional and performance requirements for telecommunications needed to conduct deep space research via spacecraft, and the technical methods and parameters of systems used in connection with such missions. [Edelson, 1972]

A set of deep space research missions considered probable during the 1977-2000 time period is shown in Table I. (This set is part of a larger group being studied in the U.S.)

Considerations regarding preferred frequency bands for deep space research can be found in Doc. 2/269. Interference, protection criteria and sharing are discussed in Doc. 2/279.

2. Telecommunication requirements

Deep space missions require highly reliable communication. As shown in Table I, this must be accomplished over long periods of time and great distances. The need for high e.i.r.p. and very sensitive receivers is a result of the large communication distance, as shown in Table I.

Table I. Characteristics of potential U.S. missions

Mission	Launch Year	Duration (Years)	Maximum Communication Distance ($x10^6$ km)
Jupiter/Saturn Flyby	1977	4	2962
Venus Orbiter	1978	6	259
Lunar Polar Orbiter	1980	2	0.41
Jupiter Orbiter/Probe	1982	8	917
Saturn/Uranus Flyby	1982	7	3023
Venus Orbiter Imaging Radar	1983	2-1/2	260
Mars Polar Orbiter	1984	2-1/2	396
Dual Comet Flyby	1984	1-1/2	157
Jupiter Orbiter	1987	7-1/2	964
Mercury Orbiter	1988	5	259
Saturn Orbiter	1989	8	1580
Jupiter/Pluto Flyby	1990	7-1/2	4499
Asteroid Rendezvous	1991	2-1/2	528
Jupiter/Neptune	1992	7	4620

*This Report supersedes Report 536, which is therefore cancelled.

Continuous usage of deep space communication bands is a consequence of the several missions now in existence and others being planned. Figure 1 shows how the long duration of missions to the outer planets results in the requirement for communication capability with several deep space missions at any given time. Each spacecraft must have the capability for communication with at least one earth station at all times, particularly during mission critical times such as orbit correction maneuver, planetary flyby, orbit insertion, or emergencies such as equipment malfunction. Unplanned loss of communication may result in poor mission performance and even mission failure.

In addition, each mission may include more than one spacecraft, so that simultaneous communication with several space stations will be necessary. The U.S. Mars Orbiter/Lander (Viking) mission was designed for simultaneous operation of two Earth-to-space links and three space-to-Earth links, using a single earth station. Simultaneous coordinated communication 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 science information from deep space.

Maintenance telemetering information about the condition of the spacecraft must be received whenever needed to insure the safety of the spacecraft and success of the mission. This requires a weather independent telecommunications link of sufficient capacity. The propagation properties of the current 2 GHz allocation meet the requirement. Maintenance telemetering data rates are relatively low. For example, the Mariner Jupiter/Saturn (MJS) spacecraft to be launched in 1977 will have data rates of 40 and 1200 bits per second (bits/s).

Science telemetering involves the sending of data from measurements made by the on-board scientific instruments. The scientific data are of two types: imaging (television-like), and non-imaging (general). For example, the imaging experiment on the U.S. 1975 Mars lander (Viking) consists of two facsimile cameras; non-imaging science experiments are biological, meteorological, seismological, molecular and mineral analysis. Data rates and acceptable error rates may be quite different for the two types of data.

Telemetering link capacity has steadily increased with the development of new equipment and techniques. This increase can be used in two ways: (1) to gather larger amounts of scientific data about nearby planets, and (2) to permit missions to more distant planets. A figure of merit used to show telemetering capability is shown in Figure 2. The figure of merit is the product of telemetering data rate and the square of communication distance. It was calculated for four missions: Mariner Mars 1964, Mariner Mars 1969, Viking Orbiter 1975, and Mariner Jupiter/Saturn 1977. Each represents an important step in telemetering development. If the 1977 figure of merit is applied to the proposed 1983 Venus Orbiting Imaging Radar (VOIR) mission with a communication distance of 2.60×10^8 km, a data rate of 1.5 Mbits/s might be anticipated. The imaging radar experiment will need a rate of approximately 3 Mbits/s, so an improvement in figure of merit is required.

As imaging experiments become more sophisticated, even higher bit rates will be required. This is discussed in Section 4.6, including the effect on bandwidth. [Davies, 1971]

An important contribution to telemetering has been the development of coding methods that permit operation with a lower signal to noise ratio. [Forney, 1970] 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. For U.S. deep space missions the telecommand link is required to have a bit error rate no greater than 1×10^{-5}. Commands must be received successfully, without regard to spacecraft orientation, even when the primary high gain antenna may not be pointed at 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.

Command data rates have been as low as one bit per second, with an increase to a few kilobits per second expected in the future.

The telecommand link must be relatively free from weather effects. Reliable telecommand includes the need for weather-independent maintenance telemetering to verify if commands are correctly received and loaded into command memory. The 2 GHz allocations provide weather independence.

2.3 Tracking requirements

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

2.3.1 Navigation

The basic tracking measurements for navigation are radio-frequency Doppler shift and the round-trip propagation time of a ranging signal. The measurements must be made with a degree of precision that satisfies navigation requirements [Curkendall, 1970]. Table II lists accuracy specifications for the Viking Mars Orbiter/lander and Mariner Jupiter/Saturn (MJS) flyby missions. Future requirements for longer or more difficult missions require more accurate navigation and tracking [Melbourne, 1976].

Table II. Navigation and tracking accuracy specifications

Mission	Required Navigation Accuracy	Doppler Frequency Measurement Accuracy	Range Measurement Accuracy	Earth Station Location Estimate Accuracy
Viking Mars Orbiter/lander	300 km at Mars	±0.003 Hz	±20 m	±20 m
Mariner Jupiter/ Saturn Flyby	400 km at Jupiter	±0.001 Hz	±4 m	±2 m
	1300 km at Saturn	±0.001 Hz	±4 m	±2 m

2.3.2 Radio science

Spacecraft telecommunication links can also be important to studies of propagation, relativity, celestial mechanics, and gravity [Anderson, 1973][Hennes, 1972][Michael, 1972]. Amplitude, phase, frequency, polarization and delay measurements provide the needed information. The opportunity to make these measurements depends on the availability of appropriate allocations. Within the 2-20 GHz range, 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 one or two centimetres are required for this fundamental scientific work. This ranging accuracy depends on wide band codes and the simultaneous use of multiple frequencies for charged particle calibration.

2.4 Requirements for manned deep space missions

Manned deep space missions beyond the moon have not yet been flown. The functional requirements of such a mission will be similar in kind to those for unmanned missions. The presence of human occupants in spacecraft will 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 communication. From a telecommunication standpoint, the effect of this will be an expansion of transmission bandwidth in order to accommodate the video signals. Given the link performance to accomplish the required data transfer rates, telecommunications for manned and unmanned deep space research are similar enough in concept that separate discussion is generally not required.

3. Technical characteristics

3.1 Earth stations

Deep Space Network (DSN) earth station complexes are located at approximately 120 degree longitude intervals as shown in Table III. At each complex there is one 64 m diameter antenna, two or more 26 m antennae, high power transmitters with extremely precise-frequency control, sensitive phase-locked loop receivers, and associated equipment [Reid, 1973]. The DSN is interconnected via terrestrial communication lines and fixed satellite facilities to a control center in California, U.S.A.

Table III. Location of DSN earth station complexes

Location	Latitude	Longitude	Height Above Mean Sea Level
Goldstone, Ca (USA)	35°22'N	115°51'W	1019 m (3343 ft)
Canberra, Australia	35°28'S	148°59'E	818 m (2684 ft)
Madrid, Spain	40°26'N	4°17'W	791 m (2595 ft)

Tables IV(a) through (d) list major characteristics of the earth stations. Tables IV(a) and (b) show current implementation, while IV (c) and (d) show planned performance improvements and additions. For current 26 m stations, increase in antenna size to 34 m and the addition of 8 GHz receive capability is planned to be complete at one station in each complex by 1980. The 64 m antennae are expected to be increased to 70 m by 1984. Transmit capability near 15 GHz may be in operation by 1990.

The system noise temperatures listed in Table IV are for the specified conditions. The noise temperature varies with the operating mode, weather conditions and elevation angle. This variation must be included in performance and interference calculations. The noise contribution of the earth station receiver alone is shown in curve B of Figure 3. The curve is based on current U.S. experience in the 2 and 8 GHz bands and estimates of possible implementation at the higher frequencies.

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 a simple uncooled preamplifier is typically used.

The space station has a combined receiver-transmitter, called a transponder, that 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 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 V lists major characteristics of space stations designed for the 1977 mission to Jupiter and Saturn.

The noise temperature of the space station receiver is shown by curve A in Figure 3. The curve is based on the noise temperature of the Helios spacecraft of the Federal Republic of Germany (600K at 2.3 GHz), and estimates of possible implementation at the higher frequencies.

At the present time, the power of the space station transmitter is limited by primary power available on the spacecraft, and not by transmitter technology, for the 2-20 GHz frequency range.

4. Deep space telecommunication methods

Telemetering and telecommand functions for deep space telecommunications are typically accomplished by transmission of phase modulated carriers [Viterbi, 1966]. Doppler tracking is done by phase coherent detection of the carrier. By adding a ranging signal to the modulation, the ranging function is performed. [Edelson, 1972][NASA, 1976].

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 [Curkendall, 1970]. 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. 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 measurement.

Table IV (a). Current characteristics of earth stations with 26 meter antennae

Band (GHz)	Antenna Gain (dBi)	Antenna Beamwidth (deg)	Transmitter Power (dBW)	e.i.r.p. (dBW)	(1)Receiving System Noise Temperature (K)	(1)Receiving System Noise Spectral Density (dB(W/Hz))
2.1 Earth-to-space	53	0.368	43	96	-	-
2.3 Space-to-Earth	54	0.328	-	-	33	-213

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

Table IV (b). Current characteristics of earth stations with 64 meter antennae

Band (GHz)	Antenna Gain (dBi)	Antenna Beamwidth (deg)	(3) Transmitter Power (dBW)	e.i.r.p. (dBW)	(2)Receiving System Noise Temperature (K)	(2)Receiving System Noise Spectral Density (dB(W/Hz))
2.1 Earth-to-space	61	0.146	50 56	111 117	-	-
2.3 Space-to-Earth	62	0.131	-	-	16	-217
8.4 Space-to-Earth	72	0.041	-	-	23	-215

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

(3)+56 dBW transmitter power use during spacecraft emergencies only.

Table IV (c). Expected characteristics of earth stations including planned increase in antenna size from 26 m to 34 m.

Band (GHz)	Antenna Gain (dBi)	Antenna Beamwidth (deg)	Transmitter Power (dBW)	e.i.r.p. (dBW)	(2)Receiving System Noise Temperature (K)	(2)Receiving System Noise Spectral Density (dB(W/Hz))
2.1 Earth-to-space	55	0.292	43	98	-	-
2.3 Space-to-Earth	56	0.260			22	-215
7.2 Earth-to-space	66	0.082	43	109		
8.4 Space-to-Earth	67	0.073	-	-	25	-215
15 Example	72	0.041	To be determined	To be deter-mined	35	-213
30 Example	76	0.026	To be determined	To be deter-mined	To be determined	To be determined

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

Table IV (d). Expected characteristics of earth stations including planned increase in antenna size from 64 m to 70 m.

Band (GHz)	Antenna Gain (dBi)	Antenna Beamwidth (deg)	(3) Transmitter Power (dBW)	e.i.r.p. (dBW)	(2)Receiving System Noise Temperature (K)	(2)Receiving System Noise Spectral Density (dB(W/Hz))
2.1 Earth-to-space	62	0.131	50 56	112 118	-	-
2.3 Space-to-Earth	63	0.116	-	-	16	-217
7.2 Earth-to-space	72	0.041	50 56	122 128	-	-
8.4 Space-to-Earth	73	0.037	-	-	23	-215
15 Example	76	0.026	To be determined	To be deter-mined	33	-213
30 Example	73	0.037	To be determined	To be deter-mined	To be determined	To be determined

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

(3)+56 dBW transmitter power for use during spacecraft emergencies only.

Table V. Characteristics of 1977 U.S. space station design (MJS)

Space to Earth Band (GHz)	Antenna Size (m)	Antenna Gain (dBi)	Antenna Beamwidth (degrees)	Transmitter Power (dBW)	e.i.r.p (dBW)
2.3	3.7	37	2.3	13.6	51
8.4	3.7	48	0.64	13.2	61

Earth to Space Band (GHz)	Antenna Size (m)	Antenna Gain (dBi)	Beamwidth (degrees)	Receiver Noise Temperature (K)	Receiver Noise Spectral Density (dB(W/Hz))
2.1	3.7	36	2.6	1540	-197

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.

The carrier tracking process also provides the local oscillator signal used to convert the radio frequency to the receiver intermediate frequency.

4.2 Modulation and demodulation

The radio links use phase (angle) 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 subcarrier is typically used for telemetering; for telecommand the subcarrier may be 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.

R.F. carrier and data subcarrier demodulation is accomplished by phase-locked loops. Data detection generally uses correlation and matched filter techniques.

Television and voice links for manned missions may use other modulation and demodulation techniques.

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 data bits into a larger number of code symbols in a particular way. Some examples of coding types are block and convolutional codes [Forney, 1970][Lindsey, 1973]. 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 amount to 3.8 dB (convolutional coding as used on MJS, with a maximum bit error rate of 1×10^{-3}).

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 subcarriers 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 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 0.5 MHz. The code period is 2 μs and resolution to 4 ns is readily achieved, assuming sufficient signal-to-noise ratio. This resolution is equivalent to 120 cm in two-way path length, or 60 cm in range. This meets the current navigation accuracy requirements of Table II.

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

4.6 Link bandwidth

Earth-to-space and space-to-Earth bandwidths are governed by required telemetering data rates [Davies, 1971] and ranging precision [Couvillon, 1970]. By contrast, the telecommand spectrum width is relatively narrow as a result of the relatively low data rate.

To pass a periodic square modulation waveform with no more than 0.3 dB loss, the bandwidth must include the fifth harmonic of the modulating frequency. For the telemetering signal, the radio frequency bandwidth must be wide enough to pass the fifth harmonic of the subcarrier frequency plus the fifth harmonic of the clock rate (1/2 the bit rate). With present techniques, the subcarrier frequency must be high enough to provide 1-1/2 subcarrier cycles per data bit. The total bandwidth required is therefore

$$BW = 2\left[\left(BR \times 1\tfrac{1}{2} \times 5\right) + 5 \times \tfrac{1}{2}\, BR\right]$$

$$= 20\ BR$$

where

BW = RF bandwidth

BR = bit rate

For example, a 1 Mbits/s uncoded data rate requires a 1.5 MHz subcarrier and 20 MHz RF bandwidth.

Figure 4 shows a curve representative of telemetering spectra.

As telemetering data rates increase, the need for a subcarrier to move the data sidebands away from the carrier tracking loop becomes less important. Direct modulation of the carrier may be used, requiring less bandwidth.

Increased telemetering data rates are expected in the future. For example, the surface imaging radar being developed to study the oceans of the Earth will gather data at 110 Mbits/s. When an instrument like this is used for study of other planets, the telemetering bandwidth required will be far beyond that available in current deep space allocations.

The current implementation of ranging uses square wave biphase modulation. The bandwidth required for the transmitted ranging signal is determined by the highest code frequency. The spectrum to the fifth harmonic is shown in Figure 5. A bandwidth equal to six times the code frequency is usually considered acceptable. For some deep space missions, the maximum bandwidth requirement will be determined by ranging accuracy considerations. Transmission in relatively wideband allocations in the 10-20 GHz portion of the spectrum will be necessary to meet ranging accuracy required for radio science.

Link bandwidth requirements for deep space research are based on needed bit rates for the various functions shown in Table VI.

Table VI. Required bit rates for a deep space mission

Direction and Function	Link: Weather Independent	Link: Normal	Link: High Data Rate
Earth-to-space			
Telecommand (bit/s)	1-1000	1-1000	1-1000
Computer programming (kbit/s)	1-50	1-100	1-200
Voice (kbit/s)	45	45	45
Television (Mbit/s)	1-4	1-12	6-24
Ranging (Mbit/s)	1	10	100
Space-to-Earth			
Maintenance Telemetering (bit/s)	8-500	8-500	8-1000
Scientific data (kbit/s)	0.008-115	1-500	$50\text{-}10^4$
Voice (kbit/s)	45	45	45
Television (Mbit/s)	0.2-0.8	2-8	6-24
Ranging (Ranging (Mbit/s))	1	10	100

Table VII lists the bandwidth required for these bit rates, assuming the use of techniques to minimize the width of the transmitted spectrum.

Some deep-space missions use two or more spacecraft. Table VIII shows the total required bandwidth for expected deep-space missions.

4.7 Antenna gain and pointing

For the parabolic antennae typically used in space research, the maximum gain is limited by size and by the accuracy with which the surface approaches a true parabola [Ruze, 1966]. The 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 antennae, is manufacturing precision.

Table VII. Required bandwidths for deep-space missions

Direction and function	Link: Weather Independent	Link: Normal	Link: High Rate Data
Earth-to-space			
Channel bandwidth (MHz)	4	40	400
Telecommand (kHz)	1 to 5	1 to 5	1 to 5
Computer programming (kHz)	5 to 250	5 to 500	1 to 1000
Voice (kHz)	50 to 200	50 to 200	50 to 200
Video (MHz)	1 to 4	1 to 24	6 to 50
Ranging (MHz)	4	40	400
Space-to-Earth			
Channel bandwidth (MHz)	4	40	400
Maintenance telemetering (kHz)	1 to 5	1 to 5	1 to 10
Scientific data (kHz)	0.008 to 115	1 to 500	50 to 10^4
Voice (kHz)	50 to 200	50 to 200	50 to 200
Video (MHz)	0.2 - 0.8	2 - 8	6 - 24
Ranging (MHz)	4	40	400

Table VIII. Deep space research bandwidth requirements and frequency bands, current and planned

Period of use and type of link	Total required bandwidth MHz	Suitable space research frequency bands MHz
Weather independent 1970 →	10	2,110 - 2,120 Earth-to-space 2,290 - 2,300 Space-to-Earth
Normal 1970 →	100	7,145 - 7,235 Earth-to-space 8,400 - 8,500 Space-to-Earth
High rate data 1980 (development starting in 1970s) →	1,000	Various bands above 10,000

For earth station antennae, surface deformation is caused by wind and thermal effects. As elevation angle is varied, gravity introduces additional distortion of the surface.

For space station antennae, size is limited by space available in the launch vehicle, and by the state of the art in constructing unfurlable antennae. Thermal effects cause distortion in space station antenna surfaces.

The maximum usable gain of antennae 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 IX shows typical limits on antenna performance. Figure 6 shows the gain of the 64 m earth station antennae as a function of frequency and elevation angle.

Table IX. Current limitations on maximum antenna gain

Limiting Parameter	Space Station Antennae		Earth Station Antennae	
	Typical Minimum Value	Maximum Gain	Typical Minimum Value	Maximum Gain
Accuracy of Dish surface	0.024 cm rms on a 3.7 m diameter reflector	66 dB(1) at 100 GHz	0.12 cm rms on a 64 m diameter reflector	76 dB(1) at 20 GHz
Pointing Accuracy	±0.15° (3σ)	55 dB(2)	±0.016° (3σ)	75 dB(2)

(1)Gain at other frequencies will be lower.

(2)Gain of antenna with half power beam width equal to 2 x pointing accuracy (3σ). Beam of higher gain antenna will be too narrow.

4.8 Additional radionavigation techniques

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

4.8.1 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 dependence 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 is discussed in Doc. 2/168.

4.8.2 Very long baseline interferometry (VLBI)

Accuracy of spacecraft navigation depends on the precise knowledge of earth station location with respect to the navigation coordinate system. A 3 metre error in the assumed station location can result in a 700 kilometre 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 [Rogers, 1970]. It is possible to record the quasar signals in such a way as to determine the difference in time of reception at two widely separated stations with great accuracy. Using a number of measurements the station locations can be determined to a relative accuracy of 50 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 [Reid, 1973]. Two 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 arcseconds. The improved accuracy will permit more precise navigation [Swenson, 1968].

5. Performance analysis and design margins

Table X 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 done during mission planning. The earth and space station characteristics shown earlier are used as the basis for calculating a performance margin for each telecommunication function.

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.

Table X. Performance budget. Spacecraft-to-Earth from Jupiter

Mission: Mariner Jupiter/Saturn 1977
Mode: Telemetering, 115.2 kbits/s, coded, 8.45 GHz carrier

Transmitter Parameters	
RF power, dBW (21W)	13.2
Circuit loss, dB	-0.2
Antenna gain, dBi (3.7m)	48.1
Pointing loss, dB	-0.2
Path Parameters	
Free space loss between isotropic antennae, dB 8.45 GHz, 9.3 x 10^8 km	-290.4
Receiver Parameters	
Antenna gain, dBi (64m, 30° elev angle)	72.0
Pointing loss, dB	-0.3
Weather attenuation, dB	-0.1
System noise spectral density, dBW/Hz (22.6K)	-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, dB (10 Hz)	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, dB (Effective noise bandwidth for matched filter detection of 115.2 kbits/s data)	50.6
Noise power, dBW	-164.5
Threshold SNR, dB (0.005 bit error rate)	2.3
Threshold data power, dBW	-162.2
Performance margin, dB	3.5

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Key Words

Deep space research

Telecommunications

Telemetering

Telecommand

Tracking

Equipment

Requirements

Characteristics

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Radio science

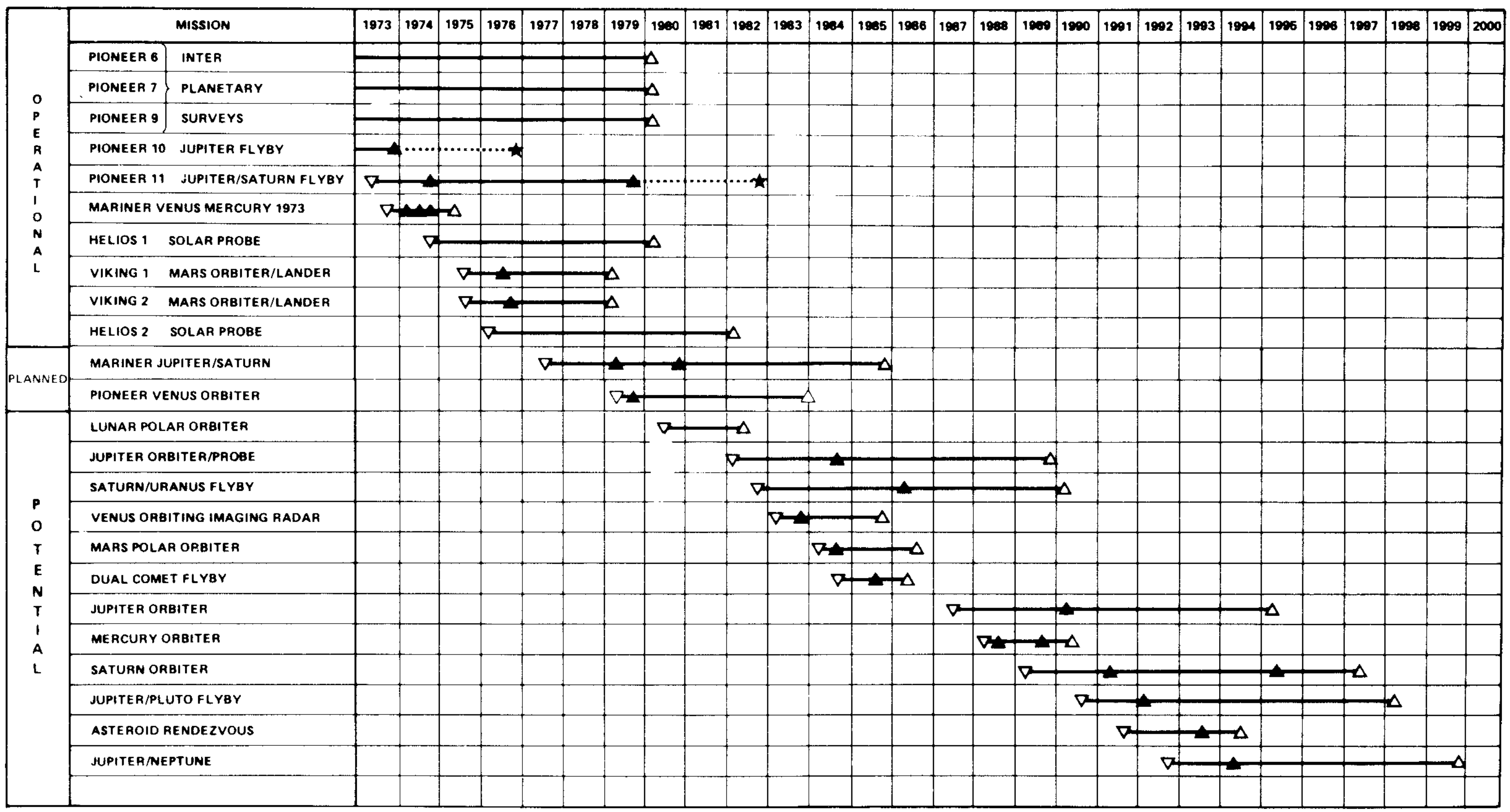

FIGURE 1

Duration of U.S. deep space missions

▽ = Launch Date
▲ = Arrival Date
△ = End of Data Date
★ = End of Mission Not Known

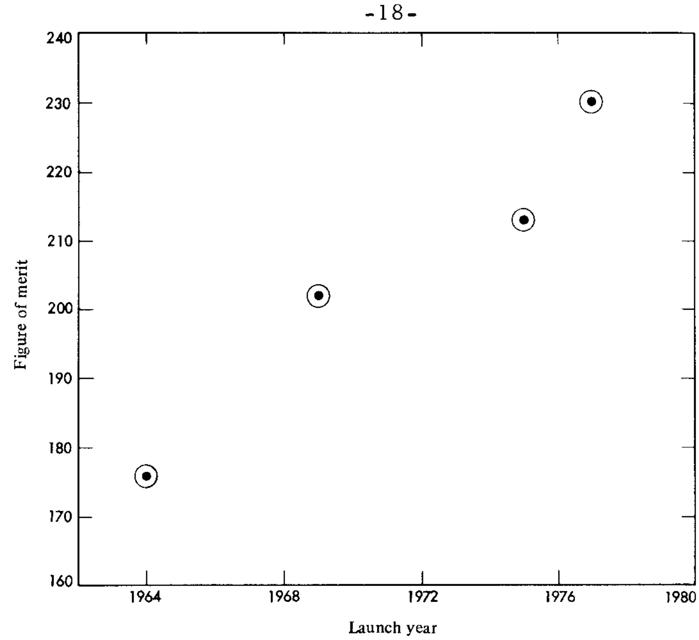

FIGURE 2

Telemetering figure of merit vs. launch year

figure of merit = 10 $\log_{10}$ (data rate x distance^2)

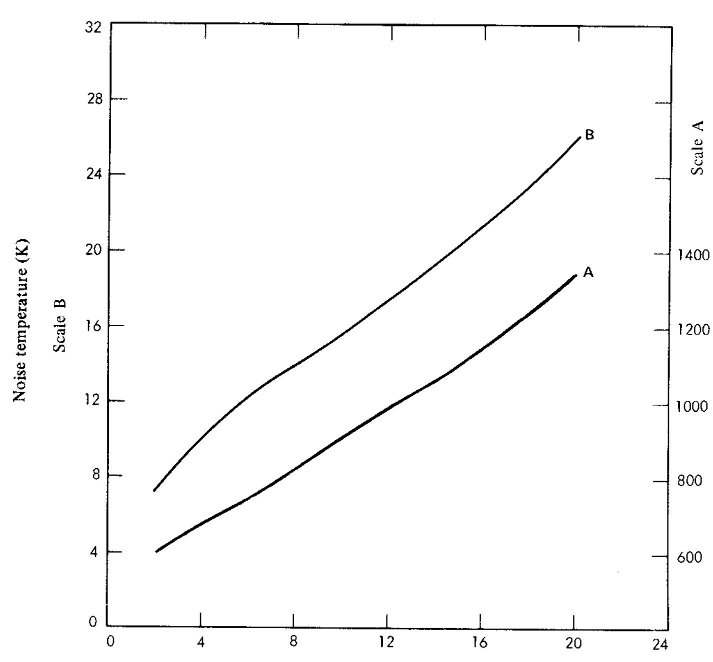

FIGURE 3

Noise temperature of receiving equipment including antenna losses

A: space station B: earth station

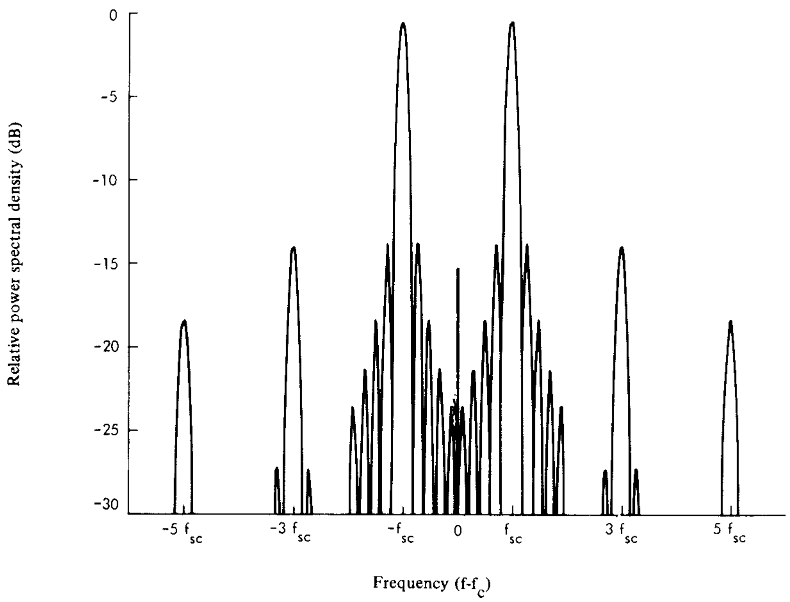

FIGURE 4

Telemetering power density spectrum (Space-to-Earth)

f: Frequency
f_c: Carrier frequency
f_{sc}: Subcarrier frequency

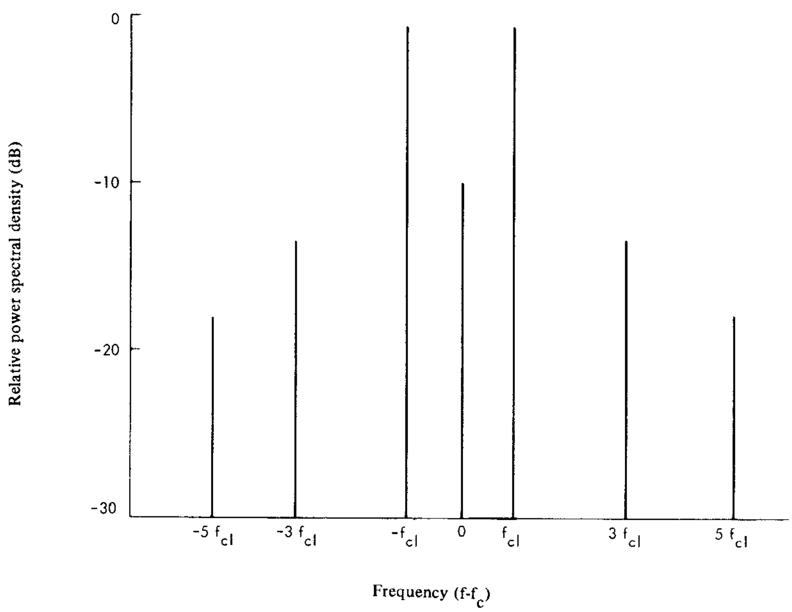

FIGURE 5

Ranging Power density spectrum (Earth-to-Space)

f: Frequency
f_c: Carrier frequency
f_{cl}: Ranging clock frequency

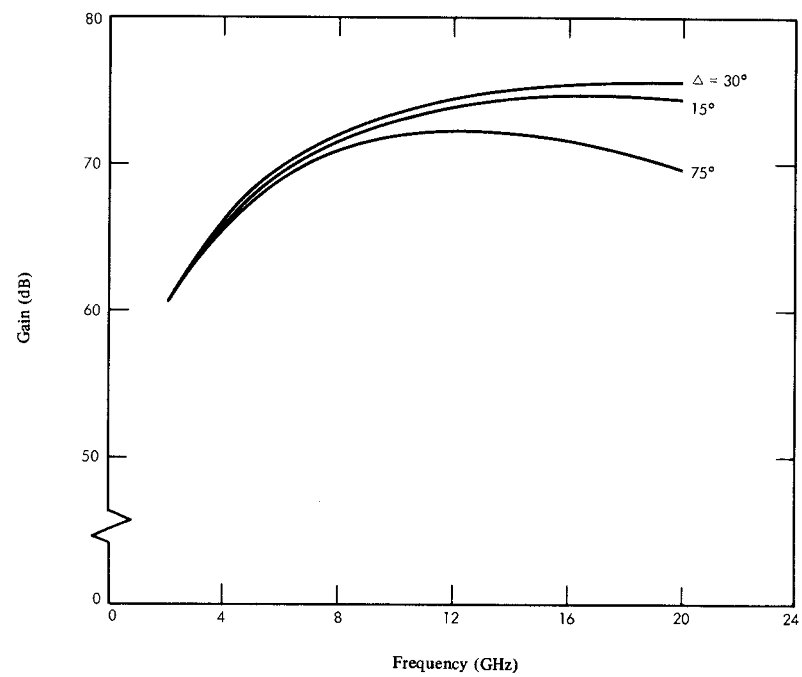

FIGURE 6

Gain of 64m earth station antenna

Δ = elevation angle of earth station antenna