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Bell Telephone Laboratories
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DEEP SPACE COMMUNICATION AND NAVIGATION STUDY

Volume 1—Summary

May 1, 1968

FINAL REPORT

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On behalf of Western Electric Company, Incorporated
For National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland

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FINAL REPORT
Contract No. NAS 5—10293
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ABSTRACT

This study provides a comparison of alternative means for high data rate communication (about 10^6 b/s) from deep space probes, and indicates the extent to which orbiting spacecraft can aid deep space navigation. Emphasis is on the communication problem. A special effort has been made to delineate practical and theoretical constraints on communication from a distance of 1 to 10 AU at microwave, millimeter, and optical frequencies (1 to 100 GHz and 20 to 0.2 microns wavelength), and to indicate promising avenues for extending the art.

The interrelationship between fundamental theory, device characteristics, and system performance has received particular attention in this study. Specific missions have been synthesized, and problems of visibility, Doppler variation, handover, acquisition, tracking, and synchronization have been investigated in order to discover the limitations imposed by practical system considerations.

This study was initiated and directed by Ira Jacobs.

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VOLUME I

SUMMARY

1. PURPOSE AND APPROACH OF THE STUDY

1.1 Purposes and Scope

The purposes of this study are (1) to compare alternative means for high data rate communication (about 10^6 b/s) from deep space probes (circa 1980), and (2) to determine the extent to which orbiting spacecraft can aid deep space navigation. Emphasis is on the communication problem. A special effort has been made to delineate practical and theoretical constraints on deep space communication (1 to 10 AU) at microwave, millimeter, and optical frequencies (1 to 100 GHz and 20 to 0.2 microns wavelength), and to indicate promising avenues for extending the art.

There have been a number of studies[1-5]* of optical deep space communication systems, and comparisons have been made of the relative merits of optical and microwave systems.[6-12] Areas that are adequately covered in the literature are treated only briefly here; emphasis has been given to areas which, it is felt, have been inadequately treated in the past.

1.2 Approach

The interrelationship between fundamental theory, device characteristics, and system performance has received particular attention in this study. Specific missions have been synthesized, and problems of visibility, Doppler variation, handover, acquisition, tracking, and synchronization have been investigated in order to discover the limitations imposed by practical system considerations.

The intent of the study has been to provide the information necessary for the engineer who must develop the most cost effective communication system for a specific deep space mission. Hence, its primary value lies in the graphs, equations, and discussions of the various important system parameters, tradeoffs, and problems. The report would not be complete, however, if some attempt were not made to compare microwave and optical means for providing deep space communications for some canonical mission. This is a dangerous comparison to make because any set of canonical assumptions is bound to include some that are inconsistent with almost any specific mission. It is impossible to develop the most cost effective mission without full knowledge and understanding of its specific purposes. But this comparison between "microwaves and optics" has become a touchstone in the field of communication research.

The value of the particular comparison made in this report lies less in the numbers than in the fact that it provides some guidance for the communication engineer in using the information contained in the study.

The viewpoint adopted in the various comparisons may be called "optimistic conservatism." There is a certain inconsistency between the time period assumed and the conservative viewpoint, since technological breakthroughs (such as new, more efficient means for generating and detecting signals at new frequencies) are almost sure to take place in the next 5 to 10 years. (As they occur, of course, their impact can be measured against the existing techniques discussed here.) But meaningful comparisons can only be made between existing or gently extrapolated techniques and devices. On the other hand, many of the devices and techniques assumed here exist now only in the laboratory; long lifetime, reliability, space adaptability, etc. have not yet been demonstrated. These problems are discussed appropriately.

2. REPORT OUTLINE

The report is in three volumes: Volume 1, Summary and Conclusions; Volume 2, Communication Technology; and Volume 3, System Considerations, including the navigation study.

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*Representative references are cited throughout the report, but no attempt is made to give a complete bibliography on the subject, nor has a direct critical review of the literature been included. References are listed at the end of each chapter.

Volume 1 describes the basic purposes of the study and summarizes the principal results and conclusions. It includes evaluations of the state of various technologies, and provides some measure of the relative value of R&D programs directed toward the improvement of deep space communications.

Volume 2 provides a "detailing of the technology" at microwave, millimeter, and optical (infrared and visible) frequencies. It was originally intended to cover microwave technology and millimeter wave technology in separate chapters, but the division was found to be arbitrary and some topics – notably space and ground antennas (Chapter 1) and low noise receivers (Chapter 2) – are covered for both the microwave and millimeter frequencies in a single chapter. Chapters 1 and 2 also contain considerable material on atmospheric propagation and noise. In Chapter 1 the emphasis is on basic effects of rain attenuation and sky noise applicable to both high microwave and millimeter frequencies; Chapter 2 includes considerations specific to millimeter frequencies.

Greatest effort was devoted to the question of optical communications, which is discussed in Chapters 3 and 4. The increased emphasis reflects the greater uncertainties inherent in the newer technology, rather than any bias towards optical communications. Chapter 3 is concerned largely with specific device aspects, with emphasis on the characterization (i.e., what parameters are of importance for deep space applications) and evaluation of lasers, modulators, and detectors. Attention is also given to the quality (tolerance) and present cost of the large optics required for optical transmitters and receivers.

In Chapter 4, optical communications are considered in a general parametric sense. The emphasis here is on atmospheric effects on propagation, and on acquisition and tracking techniques. Attention is also given to a comparison and evaluation of various modulation and detection techniques.

Specific system comparisons are made in Chapter 5. A Mars orbiter is considered, and mission parameters (e.g., visibility) which directly influence the communications are analyzed. System performance is evaluated in the microwave, millimeter, and optical frequency regions. The approach taken in both the microwave and millimeter regions is to minimize spacecraft weight for a given effective radiated power (ERP) and to determine performance as a function of both spacecraft weight and ground antenna cost. In the optical region, it is more a question of what technology will allow than optimization with respect to a given parameter. Comparisons are made of systems employing a satellite receiver with those involving direct transmission to Earth, and heterodyne systems at 10.6 microns are contrasted with direct detection systems at 0.53 micron.

The navigational aspects of the study are covered in Chapter 6. There are two interrelated general areas of investigation: (1) the use of optical angle information for better trajectory information, with emphasis on the determination of Mars transfer trajectories, and (2) the use of space vehicles for navigational aids, with emphasis on terminal navigation near Mars.

3. SUMMARY AND CONCLUSIONS

3.1 Microwave and Millimeter Systems

The factors affecting communication at microwave and millimeter wavelengths are considered in Chapters 1 and 2, respectively. These chapters are summarized in this section.

3.1.1 Space Transmitters

Space transmitters are treated in Chapter 1, Section 2 and Chapter 2, Section 1. Multiple-cavity traveling-wave tubes (TWTs) and klystrons are the primary candidates as high-power transmitter amplifiers.

System power efficiency is the controlling parameter in the power regime demanded by high data rate communications from deep space because the mass of prime power generators dominates that of the transmitter equipment.

It is realistic to assume that 2 to 6 GHz space-qualified klystron amplifiers can be developed having: (1) reliability and lifetime commensurate with deep space missions, (2) power output of 5 kW or more, (3) gain of 20 dB or more as required, (4) efficiency of about 40 percent, and (5) packaged weight (not including power converters) of about 16 lb. These devices typically have considerably more bandwidth than necessary for this application.

Impressive powers and efficiencies have also been reported with coupled-cavity TWTs at frequencies in the millimeter region. At 35 GHz a design goal of 1 kW output, 40 percent efficiency, and packaged weight of 25 lb would be realistic. Power amplification at frequencies between 6 and 35 GHz may be approximated by linear interpolation within the accuracy of these estimates.

The principal difficulty in achieving high power at millimeter wavelengths is the cooling problem caused by the small dimensions. Thermal dissipation problems are serious even at considerably lower power levels. (Mariner experiences difficulty in dissipating 75 watts.) Although heat pipe techniques and direct thermal radiation into space are promising, further design work is required before high-power space systems can become a reality.

For distances from the sun of less than 2 AU, solar cells can achieve a given primary power with less weight than reactors. For large distances, the reactor is more efficient. This is illustrated in Figure 1, where weight is shown as a function of mission distance from the Sun for 1 kW of radiated power, assuming an efficiency of 40

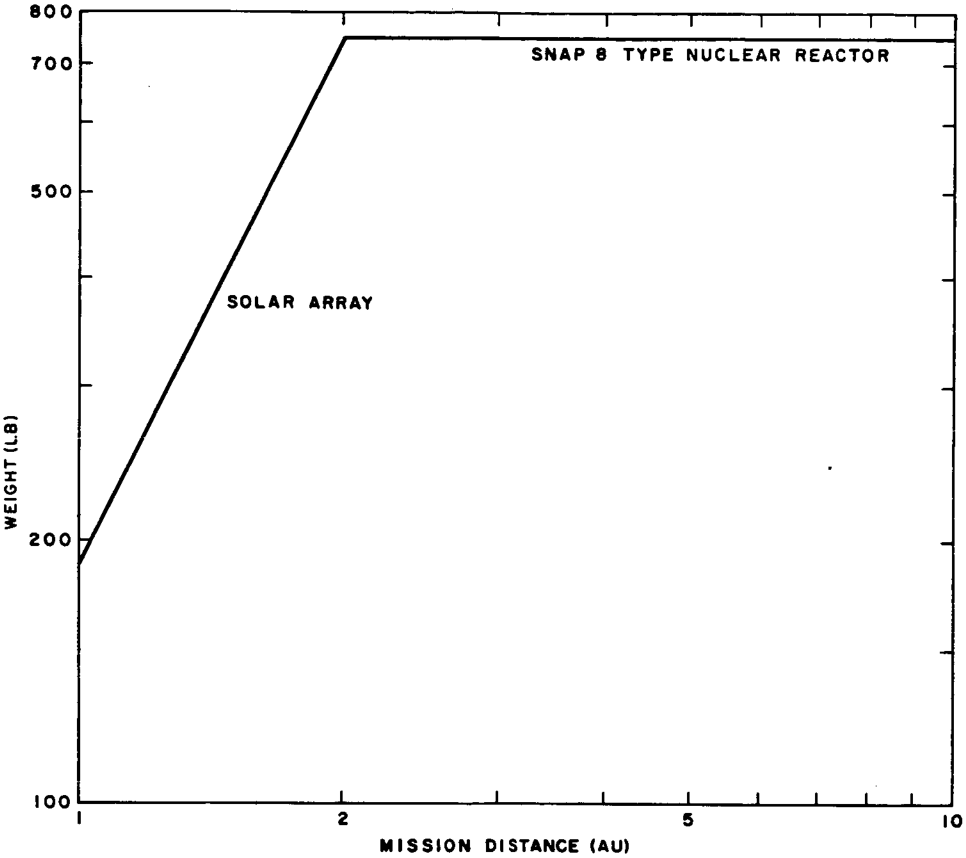

Figure 1. Minimum cost (in lb) of prime power for 1 kW transmitter output power vs. distance from sun (40 percent efficient)

percent. For mission distances of 2 AU or greater, a weight of 770 lb is required to achieve 1 kW; this includes 750 lb for the reactor, 10 lb for the power converter, and 10 lb for the tube.

3.1.2 Spacecraft Antennas

High-gain parabolic reflectors for spacecraft are characterized by several different structural concepts, few of which have actually been reduced to practice except in scale-model experiments. Typical gains of operational antennas have been 40 dB or less at gigahertz frequencies. Such antennas provide the only known actual experience in the field. The results of this study are necessarily based largely on the many studies and proposals that have been made throughout the industry for the development or construction of spacecraft antennas.

The basic performance characteristics used for comparison is power gain. The available gain is considered as a function of weight and frequency. Weight replaces cost as an independent variable here, since the cost of a high-gain antenna is a relatively minor contribution to the total cost of launching a complex spacecraft. This is not to say cost can be neglected entirely, however. The total development cost of a complicated, deployable, large diameter antenna is measured in millions of dollars, and clearly a cost trade-off must eventually enter the picture. Nevertheless, as a general comparison, antenna weight is the more natural variable to use at this stage.

No single structural concept is applicable to the range of operating frequencies, weights, tolerances, and gains that are of interest here. Five different types of antennas are considered. Together they span the entire region of interest, but there is no clear demarcation between alternatives. The five types are listed below.

Type 1 – one-piece solid surface
Type 2 – one-piece rigid structure (mesh or honeycomb)
Type 3 – petaline
Type 4 – expandable truss
Type 5 – inflatable.

The approach taken is to consider, for each type (i = 1 to 5), weight W_i (lb) and surface tolerance ϵ_i (mm) as a function of diameter D (ft).

$$W_i = \alpha_i D^{n_i} \tag{1}$$

$$\epsilon_i = \beta_i D^{m_i} \tag{2}$$

The gain is then computed using

$$G \approx 0.7 \left(\frac{\pi D}{\lambda}\right)^2 \exp - \left(\frac{4\pi\epsilon}{\lambda}\right)^2 \tag{3}$$

The coefficient (0.7) accounts for the antenna illumination efficiency which is roughly independent of size and frequency for large D/λ; the exponential accounts only for surface inaccuracy. The coefficients α_i, β_i, and the exponents n_i, m_i, for the five antenna types are given in Table 1. This table was developed by careful interpretation of weights and tolerances quoted for a limited number of different specific structures. The constants are, of course, very approximate and hold over a limited range of weights and diameters. The rms surface tolerance, ϵ, restricts the frequency capabilities of some types, particularly for large diameters.

Table 1

WEIGHT-DIAMETER RELATION ($W_i = \alpha_i D^{n_i}$) AND RMS SURFACE TOLERANCE-DIAMETER RELATION ($\epsilon_i = \beta_i D^{m_i}$)

(W_i in lb, ϵ_i in mm, D in feet)

	α_i	n_i	β_i	m_i
Type 1	0.3	3	$2(10)^{-3}$	3/2
Type 2	10	1	$4(10)^{-3}$	3/2
Type 3	0.35	2	0.12	1
Type 4	0.19	2	0.06	1
Type 5	1	3/2	0.6	1

From the above relationships [Equations (1) to (3) and Table 1], gain may be computed as a function of frequency and weight for each of the five antenna types. A composite of the best results (i.e., the minimum weight over the five types for a given gain and frequency) is shown in Figure 2. For weights below 300 lb, the one-piece rigid structure (Type 2*) antenna is best. For weights greater than 300 lb and gains less than 55 dB, the expandable truss (Type 4) antenna is best. For weights greater than 300 lb and gains greater than 55 dB, the solid (Type 1) antenna is best.

It is apparent from observations of α_i and β_i in Table 1 that the expandable truss (Type 4) antenna is lighter and more accurate than the petaline (Type 3) antenna at all diameters. It should be noted, however, that considerable approximation and uncertainty are implicit in both the weight and tolerance estimates, and that specific designs must be evaluated before firm conclusions are drawn.

The conclusion that existing and presently proposed inflatable antennas (Type 5) are not desirable is occasioned both by the poorer tolerances and by the rather appreciable weight associated with the structure. The future may paint a new picture here.

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*Note from Table 1 that the Type 2 antenna is the only one of the three preferred types for which weight increases more rapidly than surface area. For such antennas most of the weight is in the supporting structure rather than the surface.

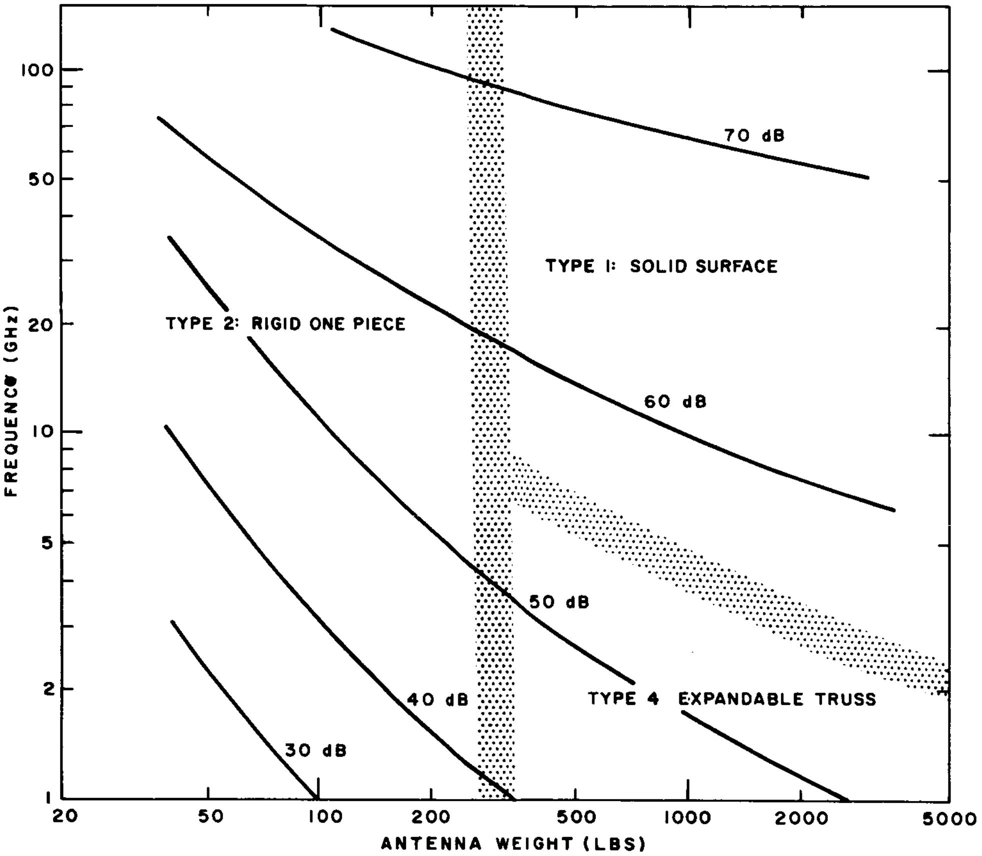


Figure 2. Composite-spacecraft antenna gain vs. weight and frequency

In conclusion, for antennas less than 25 ft in diameter, one-piece structures are desirable. At frequencies for which the tolerances are acceptable, the one-piece rigid surface is preferable to the solid surface, but as the frequency is increased it becomes necessary to ultimately employ a solid surface. For antennas in the 30 to 60 ft range, the expandable truss structure appears best.

It should also be noted that the deep space environment (particularly the thermal environment) is considerably more benign than that of an Earth satellite, and that antenna diameters larger than those discussed above are by no means ruled out. This is a technology in flux and provides room for growth.

3.1.3 Propagation and Noise

The noise temperature of the galaxy, the universe, and clear atmosphere owing to radiation from oxygen and water vapor is shown in Figure 3. Both absorption and sky temperature begin to increase appreciably beyond about 8 GHz in the presence of water vapor.

The lack of detailed knowledge of rain and cloud characteristics constitutes the real difficulty in predicting attenuation and noise increases caused by water particles in the air. Cloud attenuation coefficients (dB of attenuation per km of path, per gram per m^3 of water vapor content) are shown as a function of frequency in Figure 4. Calculation of similar coefficients for rain would require knowledge of drop size distributions along vertical paths, and reliable information of this sort does not exist. Cloud distributions obtained by satellite and rainfall measurements with arrays of rain gauges have provided some data, but data on the vertical distribution of both clouds and rain are still lacking.

At the millimeter wavelengths, both cloud and rain attenuation are appreciable. This is illustrated in Table 2 where atmospheric propagation loss is shown under clear atmospheric conditions, for dense clouds (1 gm/m^3) of 1 km in extent, for light rain (0.1 in/hr, 3 km height), and for heavy rain (1 in/hr, 3 km height). It is clear that millimeter systems cannot operate through heavy rain, but by appropriate siting and diversity, heavy rain may be avoided. For example, Weather Bureau information shows that, in the vicinity of Goldstone, California, there are about 71 hr of rain per year, with a total accumulation of 2.7 in. However, a rain rate of 0.1 in/hr is exceeded only about 4 hr per year. Furthermore, even at locations at which heavy rain does occur, recent measurements indicate that such rain is surprisingly localized, and that separations of 10 miles may be adequate to achieve significant spatial decorrelation of atmospheric attenuation above a few dB.

Section 4 of Chapter 1 contains a brief discussion of the error in angle prediction due to refraction uncertainties.

Table 2

ATMOSPHERIC PROPAGATION LOSS (dB)

60° Zenith

	2 GHz	8 GHz	16 GHz	35 GHz	94 GHz
Clear atmosphere attenuation	0	0	0.2	0.5	2.4
Dense clouds	0	0.1	0.3	2	9
0.1 in/hr rain	0	0.1	0.6	3	11
1 in/hr rain	0	1.8	12	30	60

For elevation angles greater than 10 degrees, the prediction accuracy is better than 10^{-4} radian.

The effects of phase front distortion on millimeter systems are considered in Sections 2 and 4 of Chapter 2. Maximum useful antenna diameters are somewhat arbitrarily taken to be the distance for which there is an rms phase difference of $\lambda/6$. For a 15 degree elevation angle, it is found that the maximum useful diameter is of the order of 75 meters at 35 GHz, but only about 8 meters at 94 GHz. As noted in the following section, however, tolerance and cost considerations will generally limit millimeter antennas to considerably smaller diameters.

3.1.4 Ground Receiving Antennas

Ground antennas for microwave and millimeter wave communication systems are considered in Section 5 of Chapter 1. The approach taken is to relate diameter, cost, gain, frequency, and rms surface tolerance for both exposed and radome enclosed antennas.

The gain is related to diameter (D), wavelength (λ), and rms surface tolerance (ϵ) by Equation (3). The remaining relations of interest; viz., the relation between rms surface tolerance and diameter, and the relation between cost and diameter, are empirically deduced from information available on existing and proposed installations. Existing data indicate that $\epsilon \sim D^{3/2}$, with the proportionality constant being three times larger for exposed antennas than for antennas under a radome. A "standard tolerance," ϵ^*, is defined by the relation

$$\epsilon^* = \alpha D^{3/2} \qquad (4)$$

where α is given in Section 5 of Chapter 1.

A simple empirical relationship (not expressible by a simple power law) can be obtained between the cost and diameter of antennas that satisfy the standard tolerance relation. A quality factor can then be introduced which relates a change in rms surface tolerance to a change in cost. This heuristically chosen factor causes costs to increase exponentially when tolerances better than ϵ^* are required, and to reduce only slightly when tolerances are relaxed.

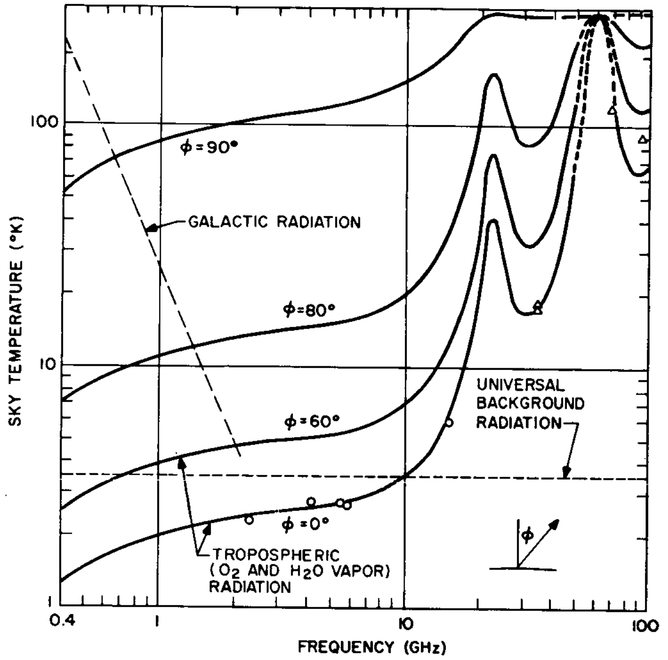


Figure 3. Sky temperatures vs. frequency

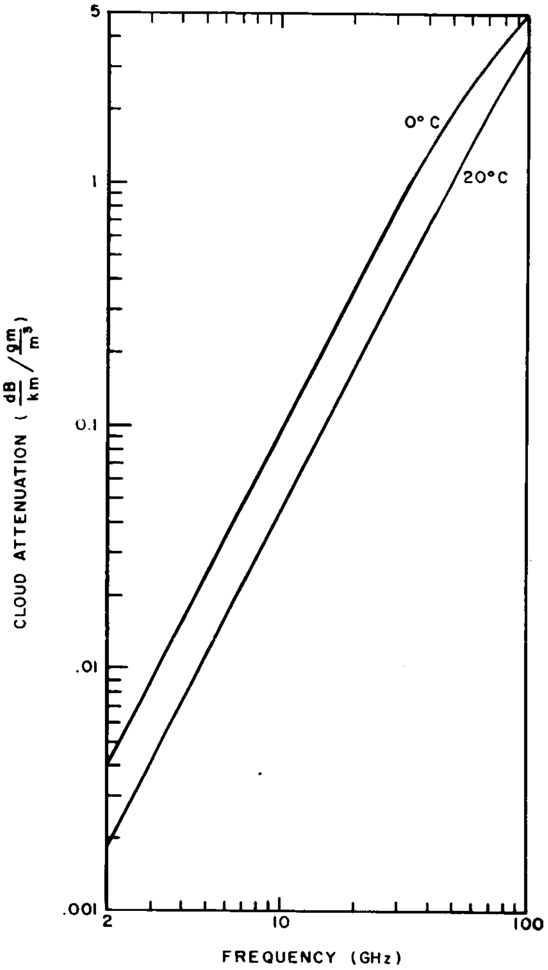


Figure 4. Cloud (fog) attenuation coefficients

The model outlined above and described in detail in Chapter 1, Section 5, results in three equations relating the five parameters: cost, gain, diameter, rms surface tolerance, and frequency. For a fixed cost and frequency there is a diameter which achieves maximum gain. Above this diameter a gain-limited antenna cannot be achieved with the given cost. Below this diameter, although the gain limit can be achieved, gain falls off as diameter decreases.

In Figure 5 the maximum gain is shown as a function of frequency for fixed costs of \$1 million, \$5 million, \$10 million, and \$20 million. For 8 GHz and below, $G \sim f^{1.6}$. Since receiving effective area, A_e, is given by

$$A_e = \frac{\lambda^2 G}{4\pi} \qquad (5)$$

it follows that $A_e \sim f^{-0.4}$. For 16 GHz and above, $G \sim f^{1.1}$. Consequently $A_e \sim f^{-0.9}$.

Effective area decreases more rapidly at the higher frequencies because of surface tolerance difficulties.

3.1.5 Low-Noise Receivers

Low-noise receivers are considered in Section 3 of Chapter 2. The input noise temperature of maser amplifiers at S-band is 5°K and similar temperatures may be achieved at X-band. A 35 GHz maser has been operated with a noise temperature of 20°K, with promise of reducing this to 10°K. Although higher frequency masers exist, little effort has been devoted to masers in the millimeter region.

Masers require operation at liquid helium temperature. Parametric amplifiers, on the other hand, may be designed to operate in either a cooled or uncooled mode. The paramp is the most sensitive microwave receiver for operation at room temperature where noise temperatures of the order of 150°K are achievable. Cooled paramps may achieve noise temperatures as low as 20°K. It is clear, however, that parametric amplifier receiving systems cannot achieve the low system noise temperature (25°K) that can be achieved at S-band with a maser receiver and careful antenna design.

3.1.6 Communication Performance

The above factors; viz., the transmitter power, transmitting antenna gain, propagation loss, receiving effective area, and system noise temperature, permit the calculation of the received signal-to-noise ratio in a given bandwidth. For digital communication systems, the bit rate is then given by the bandwidth in which the signal-to-noise ratio is E/N_0, where E/N_0 is the ratio of energy per bit to noise spectral density. In Section 6 of Chapter 1, digital modulation systems are compared on the basis of the E/N_0 required to achieve a given error probability (P_e). Particular attention is given to biorthogonal modulation systems. These are most readily implemented by coding a block of L bits into a sequence of 2^{L-1} binary digits (Reed-Muller code) and using this sequence to phase-modulate an rf carrier. The basic receiver operation consists of a phase detector followed by 2^{L-1} accumulators (coherent matched filter).

The E/N_0 required to achieve $P_e = 10^{-5}$ is shown as a function of L in Figure 6. Although E/N_0 is a monotonic decreasing function of L, both complexity and bandwidth limitations (see Figure 7) dictate against very large values of L; values of L between six and nine with E/N_0 requirement between 5 and 6 dB are indicated.

A difficulty in the use of large values of L is that the output of 2^{L-1} accumulators must be compared in a time that is small compared to the bit period. To circumvent this computational problem in the receiver, a simple threshold demodulation scheme is analyzed and shown to come within about 2 dB of the optimum detector. Furthermore, threshold demodulation permits an interesting option. By raising the threshold, the error probability can be made negligibly small at the expense of an increased deletion probability. It is shown, for example, that for $P_e = 10^{-5}$ and $L = 12$, $E/N_0 = 4.3$ dB if a 1 percent deletion probability is allowed.

Convolutional coding with sequential decoding is also considered in Section 6, Chapter 1. Although sequential decoding appears to yield about 2 dB smaller E/N_0 than biorthogonal (or other block codes), it appears to have two disadvantages relative to the biorthogonal system:

1. The variable computational requirements make it difficult to engineer a high data rate system.
2. Sequential decoding requires that the bulk of the computation be done sequentially, whereas biorthogonal (or other block-coded) systems allow considerable parallel operation.

Although it is not possible (on the basis of this study) to recommend a specific modulation or coding system, it is apparent that there are a number of practical techniques for achieving reductions in E/N_0 of 4 to 6 dB relative to the best uncoded binary modulation systems. It is furthermore shown that the performance limits are generally imposed by the computational requirements on the receiver and, if moderate deletion rates are allowed (in either block or convolutional codes), the computational problem may be greatly reduced.

3.2 Optical Technology

The discussion of the components and techniques required for optical communications which appears in Chapter 3 is summarized in this section. Included are lasers, optical modulators, transmitter and receiver optics, pointing of transmitter optics, detectors, filters, and amplifiers.

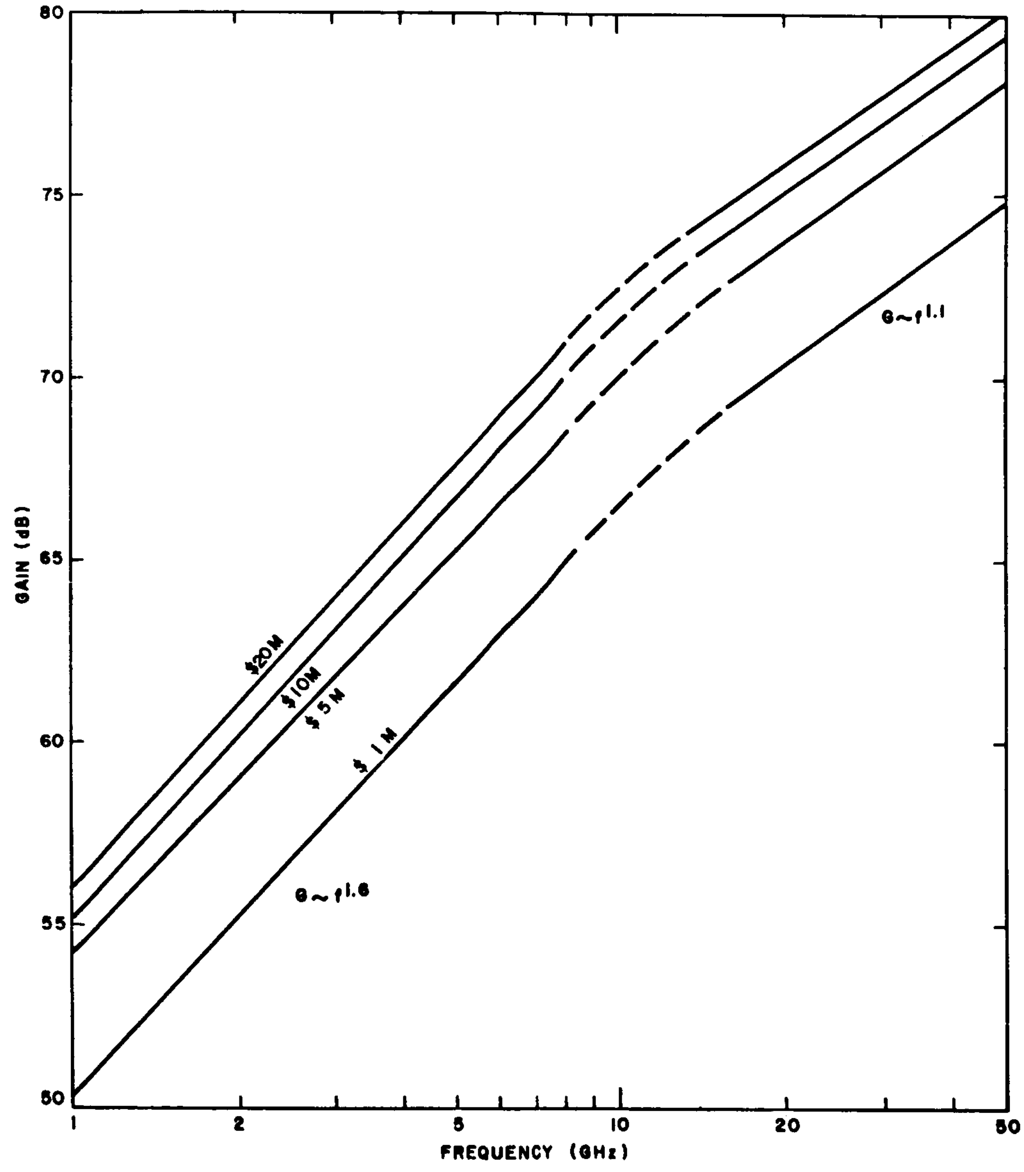


Figure 5. Maximum gain of large fixed-cost ground antennas

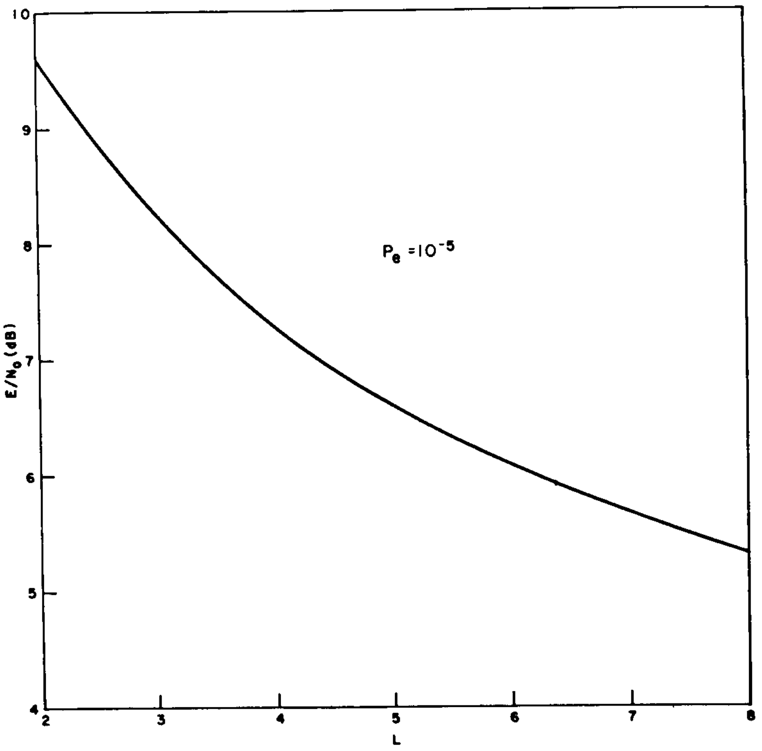


Figure 6. Signal-to-noise ratio vs. code block length (2^{L-1} binary digits) for biorthogonal modulation system

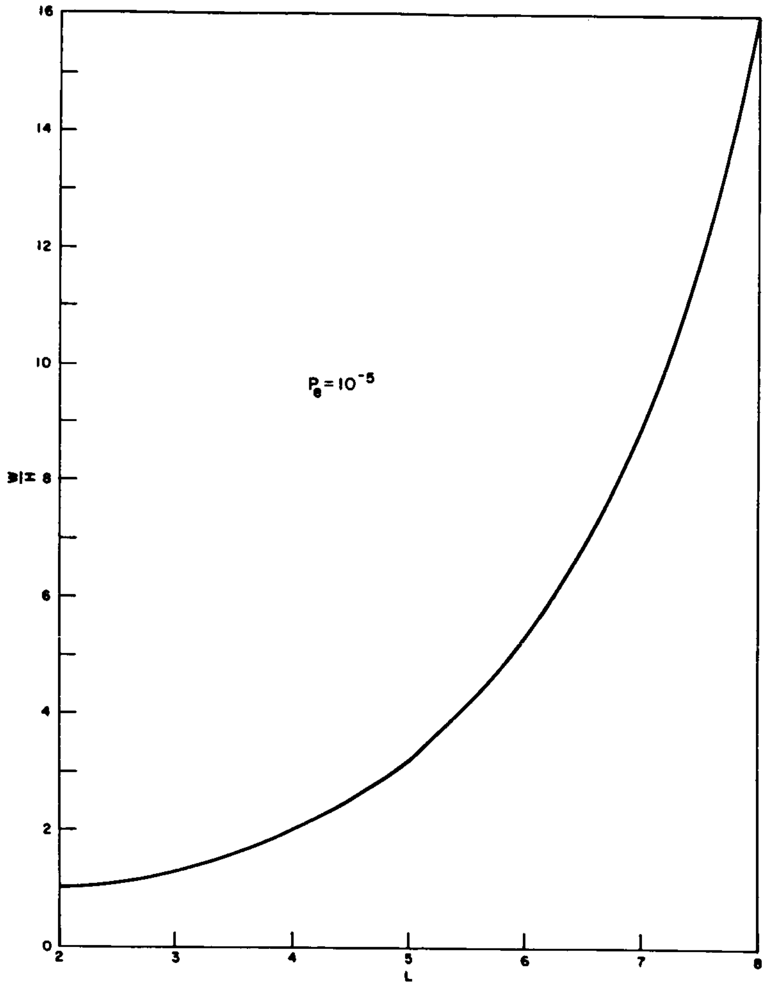


Figure 7. Cycles per bit vs. code block length, biorthogonal modulation

3.2.1 Lasers

Leading candidates for an optical deep space communications transmitter are argon, second harmonic generation (SHG) Nd:YAG, Nd:YAG in the fundamental mode, and CO_2 lasers. It is proposed that laser operation be restricted to the lowest order mode TEM_{00} to achieve maximum transmitter gain. State of the art output power levels and overall power efficiencies for the four lasers are:

Laser and Wavelength	P_{out} (TEM_{00})	Efficiency (excluding cooling) (percent)
Argon (0.48 and 0.51μ)	3 watts	0.03
SHG Nd:YAG (0.53μ)	6 watts	0.18
Nd:YAG (1.06μ)	12 watts	0.36
CO_2 (10.6μ) – flowing gas	10 watts/ meter	8

Output power of the CO_2 laser increases approximately linearly with the discharge length. Efficiency of a nonflowing CO_2 laser is ~5 percent. Improvements in P_{out} and efficiency are expected in the future for all types; the potential increase is greatest for Nd:YAG (via more efficient pump lamps) and least for CO_2 because of its already high efficiency. Noteworthy advantages of the Nd:YAG are (1) laser medium is solid state (consequently, its deterioration with life should be less than for gaseous media) and (2) overall size is smaller.

At present, the life of these lasers is in the 1000 hr range for all four types, with ~10,000 hr anticipated in the future. Table 3 summarizes life and life-limiting factors. Accurate weight prediction is difficult at the present stage of development. Nevertheless, weight estimates, based on very limited data, are 100, 25, and 50 lb for argon, Nd:YAG, and CO_2 respectively including power converters, magnets, etc. but excluding cooling systems or gas supply (if a flowing CO_2 laser is used).

3.2.2 Modulators

The electro-optic modulator currently is the best candidate for use in an optical deep space transmitter. Acousto-optic modulators are promising, but relevant device development is only in the early stages. Known wideband and low drive power magneto-optic materials work only in the 1.2 to 1.3 micron range. For 0.5 and 1.06 micron wavelengths, $Ba_2NaNb_5O_{15}$ is the most promising electro-optic material (subject to future improvements in crystal quality); GaAs is currently the best material at 10.6 microns. Reasonable objectives for a modulator design at a megabit data rate and at 0.5 or 1.06 microns are:

1.	Material	$Ba_2NaNb_5O_{15}$
2.	Modulation	Binary polarization
3.	Output polarization	Circular righthand ("0") or lefthand ("1")
4.	Reactive driver power	10^{-3} watt
5.	Total driver power	5 watts
6.	Weight	8 lb
7.	Insertion loss	1 dB

Biorthogonal phase shift modulation with circular output polarization is recommended at 10.6 microns, for which the reactive driver power is about 40 watts with GaAs. Available data are insufficient to specify total driver power or weight for this modulator type. Investigation and development of materials with electro-optic coefficients at 10.6 microns higher than that of GaAs are especially needed.

Promising materials for acousto-optic modulators are $LiNbO_3$ or TiO_2 (rutile) at 0.5 micron, GaP or As_2S_3 at 1.06 microns, and Te at 10.6 microns. Two important factors which might make this modulator competitive with the electro-optic type, and which currently are receiving developmental attention, are more efficient acoustic transducers and optimum acoustic column design.

3.2.3 Transmitter-Receiver Optics

Analysis of cost data available on existing telescopes shows that the relation $C \sim D^n$ holds reasonably well for a diameter range of 4 to 400 inches. C is the cost, D the diameter, and the exponent n is 2.5 to 3 (Figure 8). This result agrees closely with radio telescope costs for which case n is 2.5 to 2.7. A 1-meter diameter, $\lambda/50$ surface-figure mirror for an optical space vehicle transmitter appears attractive as a compromise between high gain and moderate weight (800 to 1000 lb). Weight of diffraction-limited telescopes increases extremely rapidly with D for D above 1 meter. This is primarily because of the active optics required to maintain the surface figure. Coherent, large diameter, Earth based, optical receivers are considered only for a 10.6 micron wavelength, for which the cost estimated by Perkin-Elmer of a 120 inch diameter unit is about $\$4 \times 10^6$. Experimental measurements of the coherence diameter of a 10.6 micron beam passing vertically through the atmosphere are required, however, to establish whether such a large diameter can be fully utilized in a ground-based receiver. (See Section 3.4.5 for comparison of ground vs. satellite receiver.)

Table 3

LIFE LIMITATIONS OF LASERS

	Argon	Nd:YAG	CO_2
Life at present (hr)	1000-2000	1500	No known limit (flowing) 300-1000* (static)
Primary life limitation	Discharge tube structure	Pump lamp	Gas dissociation and cleanup (static)
Other life limitations	1. Cathode 2. Gas cleanup		
Means of increasing life	1. Segmented metal discharge tube 2. Hollow cathode 3. Argon reservoir and/or automatic leak valve 4. Minimum electrode sputtering	1. New lamp types 2. Development of longer life tungsten lamps	1. Electrode and discharge wall materials to minimize gas cleanup 2. Oxidizing agents to convert CO into CO_2

*Life data in the range of 3000 to 5000 hours have been reported for static CO_2 systems; however, the discharge conditions for the longer life were such that the power efficiency was much less, ~1-2 percent, instead of the 7 to 10 percent given in Table 4.

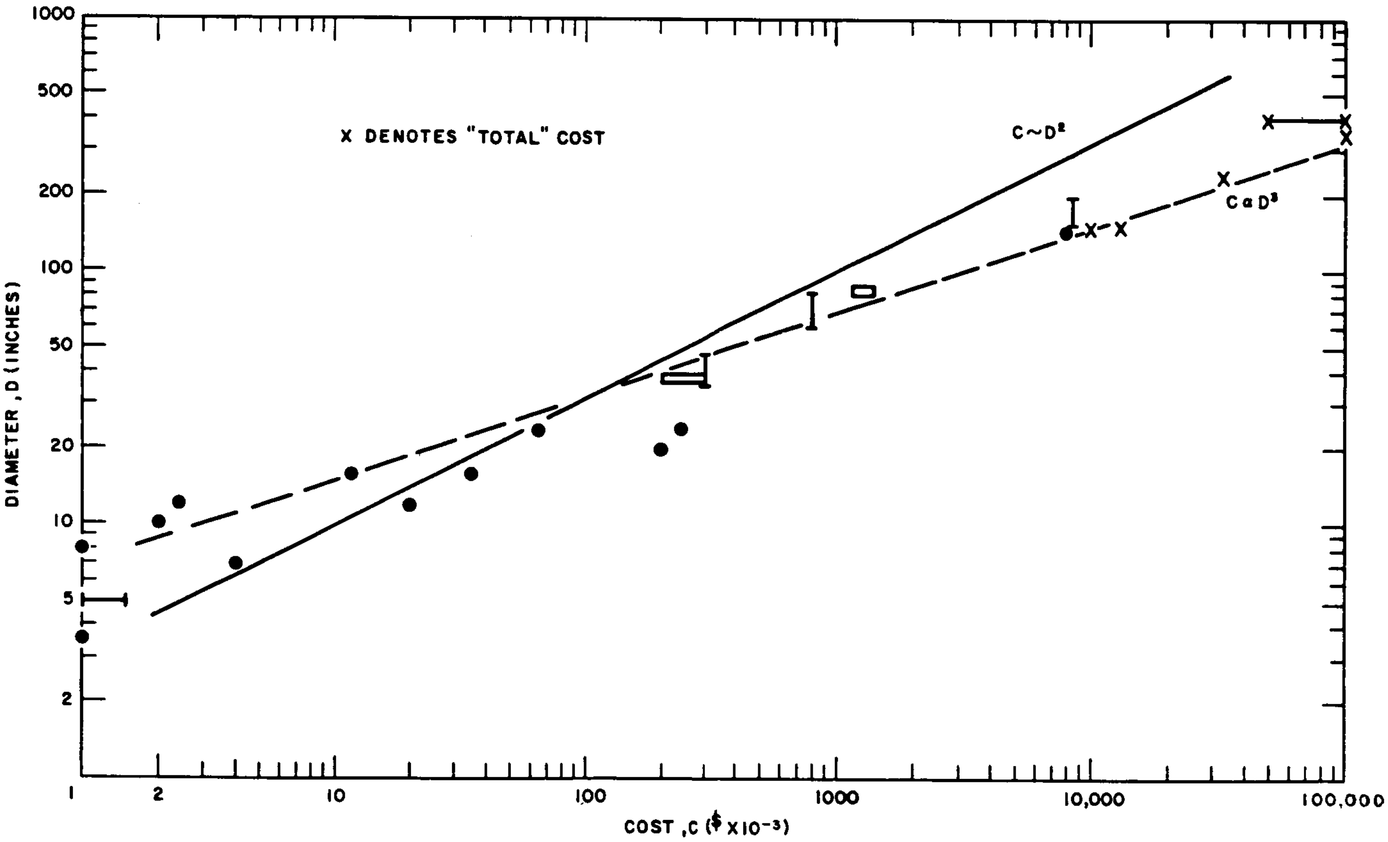


Figure 8. Telescope cost as a function of diameter

Incoherent optical receivers are proposed for 0.5 and 1.06 microns. Analysis of the surface figure dependence shows that millimeter wave tolerances are inadequate unless surfaces with exceptionally large correlation lengths (several meters) can be produced. For a more typical correlation length of 10 cm, the surface errors must be less than 2 microns to obtain a 10^{-4} radian field of view.

A very critical problem affecting performance of both transmitter and receiver optics is the thermal environment. It is especially severe for ground receivers which must function during the daytime, when atmospheric turbulence effects are usually greatest.

3.2.4 Transmitter Pointing Requirements and Beacon Performance

The desired pointing accuracy for a 1 meter aperture at 0.5 micron wavelength is about 0.1 microradian. If an optical beacon is Earth-based, beacon beamwidth must be on the order of 0.1 milliradian; more experimental data on random atmospheric refraction of laser beams must be obtained to establish the minimum obtainable beamwidth of an Earth-based beacon. Tracking accuracy is adequate to compute the point ahead offset, for compensation of velocity aberration (Bradley effect), to better than 0.1 microradian precision. Means for implementing the offset to this accuracy on a spacecraft require further investigation; any such system should include no noisy moving parts such as gear trains or motors.

A pulsed Nd:YAG Q-switched laser operated in the SHG mode at 0.53μ (preferred) or 1.06μ (second choice) is judged to offer the best performance as an Earth-based optical beacon transmitter. Repetition rates of 100 p/s, a 10 nanosecond pulse width, and an average power of 1 to 10 watts are realistic objectives.

3.2.5 Optical Filters

Three filter types are considered:

1. Thin-film
2. Fabry-Perot
3. Birefringence.

The thin-film and Fabry-Perot are preferred for space use. Table 4 summarizes filter characteristics at visible and 1.06 micron wavelengths. The Fabry-Perot filter has a narrower passband width, but it requires a blocking filter and more precise temperature control. At 10.6 microns, only thin-film filters are presently available for which the minimum passband is about 750Å.

3.2.6 Optical Detectors

Electrostatic photomultiplier detectors offer the lowest noise performance at 0.5 and 1.06 microns. Substantial reductions in dark noise are achieved by cooling the photo-cathode. For a megabit data rate, the dark noise is below the quantum limit at both 0.5 and 1.06 micron wavelengths for a 110°K cathode temperature. Doped-Ge cooled photoconductors provide the best detector performance at 10.6 microns. Table 5 shows characteristics of detectors suggested for the various preferred wavelengths.

Table 4

FILTERS FOR VISIBLE AND NEAR-INFRARED

Description	Thin-Film	Fabry-Perot	Birefringence
Bandwidth (3dB)	1.5Å at 6328Å	0.5Å at 6328Å 1.6Å at 1.06μ	0.125Å at 6582.8Å
Blocking filter requirement	None	Yes, less than 15Å wide	Yes, less than 32Å wide
Peak transmission (percent)	~30	~50 (with blocking filter)	~10 (with blocking filter)
Size: Aperture	Few inches	Few inches	~1.5 inches
Thickness	Thin (~mm)	Thin (~mm)	Few inches
Angular field of view (degrees)	~5	~2	~2
Temperature stability	~0.1Å/°C	0.05Å/°C	1° retardation change per 0.01°C. Consequently temperature stability of better than 0.01°C is required.
Tunability	Yes	Yes	Yes

3.2.7 Optical Amplifiers

Only limited gain data are available for 0.5 micron argon and 1.06 micron Nd:YAG amplifiers; however, they suggest that the gain is inadequate at both wavelengths for effective use in optical receivers. No amplifier exists at the 0.53 micron SHG wavelength, although the parametric amplifier principle offers a potential future possibility. Gain in excess of 50 dB is judged feasible at 10.6 microns.

3.3 Optical Communications

Communications analyses relevant to the deep space optical communications link discussed in Chapter 4 are summarized in this section. The parameters treated are background noise, atmospheric effects, pointing control, modulation, and detection schemes. Emphasis is placed on a high capacity link ($\gtrsim 10^6$ sec^{-1} bit rate).

3.3.1 Background Noise

Scattered sunlight and thermal background radiation from the atmosphere and from Mars can be a significant factor and must be considered in the design of a megabit/s information rate, Mars-Earth communication link. Direct detection systems are more vulnerable to sky background than heterodyne schemes because of the limited capability of optical filters (1Å, corresponding to 10^{11} Hz minimum bandwidth at 0.53μ).

3.3.2 Other Atmospheric Effects

The Earth's atmosphere affects deep space communication to a ground receiver by attenuation and phase/amplitude fluctuations. At 0.63μ, typical observed coherence diameter d_{coh} is a fraction of a centimeter; the theoretical maximum area to be expected is a few cm^2. Theoretical estimates of d_{coh} at 10.6μ vary from one to several meters. Both experimental measurements of d_{coh} at 10.6μ and more data at visible wavelengths (particularly in the vertical direction) are needed. Higher frequency (or fine scale) atmospherically induced amplitude and phase fluctuations will not pose serious communication problems for a receiver diameter $\lesssim d_{coh}$, but deep fading due to gross refraction and attenuation could be a serious problem with a ground-based receiver.

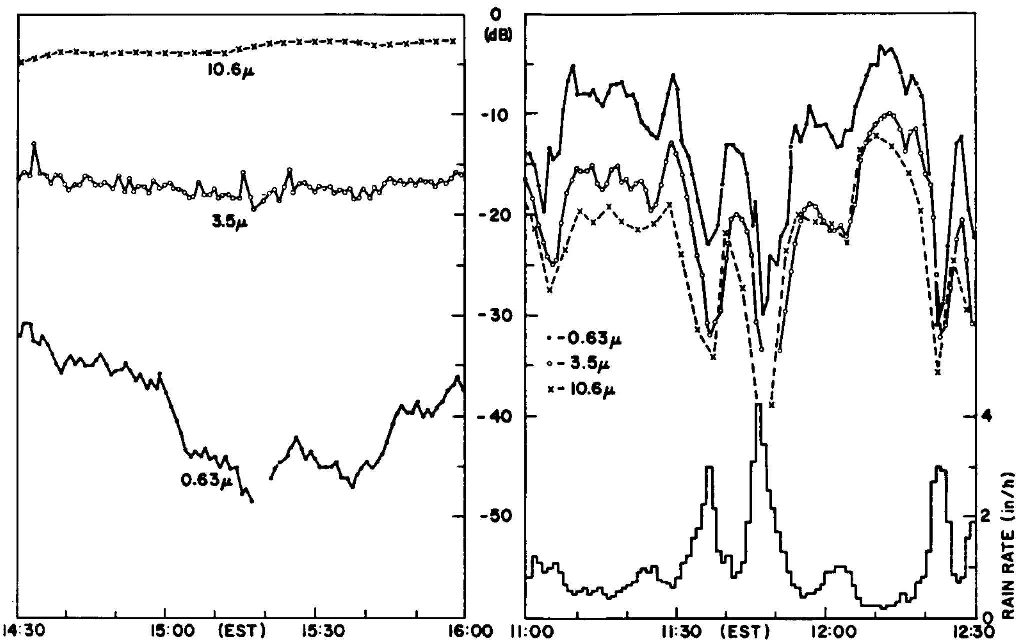
Attenuation by rain, snow, and fog has been measured at 0.63, 3.5, and 10.6μ. Theoretical analysis of precipitation attenuation yields results consistent with experiments. In fog, the attenuation decreases with increasing wavelength, whereas in rain 10.6μ radiation is sometimes attenuated more than at shorter wavelengths. Heavy fog can cause transmission loss as high as 40 dB/km at 10.6μ. In light fog, vertical transmission through the atmosphere to the ground at 10.6μ appears feasible; however, at 0.63μ, loss over the same path would be much higher and vertical transmission through anything but light ground fog could not be considered. Figure 9 shows an example of simultaneous attenuation measurements at 0.63, 3.5, and 10.6μ over a 2.6 km horizontal path for the cases of very light fog and a rain storm.

Table 5

RECOMMENDED DETECTORS

Wavelength in μ	Type of Detector	NEP in Watts/$(\text{Hz})^{1/2}$ or D* in cm-$(\text{Hz})^{1/2}$ /Watt	Detector Temperature (°K)	Comments
0.5	Photomultiplier (S-20 photocathode)	10^{-16} 10^{-18}†	300 110	NEP may be improved by decreasing effective cathode size
0.69	Photomultiplier (S-20 photocathode)	4×10^{-16} 4×10^{-18}†	300 110	NEP may be improved by decreasing effective cathode size
1.06	Photomultiplier (S-1 photocathode)	10^{-12} 10^{-15} 10^{-17}†	300 255 110	NEP may be improved by decreasing effective cathode size
10.6	Photoconductor			Photoconductor performance severely limited by background. Coherent detection preferred. Bolometers operate under BLIP condition (reached at 4.2°K for this sample). However, time response is slow (400 μsec).
	(Ge: Hg)	2×10^{10} (D*)	28	
	(Ge: Cu)	1.3×10^{10} (D*)	4.2	
	Bolometer			
	(Ge)	5×10^{10} (D*) 8×10^{11} (D*)	4.2 2.15	

† Estimated value and not measured.



(a) VERY LIGHT FOG (1-4-67)

(b) RAIN STORM (9-21-66)

Figure 9. Measurement of 2.6 km transmission loss relative to signal level in clear weather (in dB)

3.3.3 Pointing Control

Three levels of pointing control on the space vehicle are required to achieve 10^{-6} to 10^{-7} radian pointing accuracy. Proposed pointing precisions, in order of increasing accuracy, are (1) ~1 degree for the entire space vehicle, (2) ~1 arc-min (3×10^{-4} radians) for the transmitter telescope, and (3) ~10^{-6} to 10^{-7} radian accuracy for a tracking transfer lens which autotracks an Earth-based optical beacon. Point-ahead offset may be computed from orbit data and implemented in the space transmitter pointing control system in an open loop mode. An optical beacon appears essential for achievement of ~0.1 arc-sec pointing accuracy.

Optical autotracking is a critical problem that deserves special attention. Analysis indicates that the required power of an Earth-based CW beacon for a Mars-Earth link exceeds the capability of available lasers. Consideration of a pulsed laser beacon with time gating shows that its performance is better than the CW type but its feasibility presently is marginal at 1 AU range. Requisite pulse energy is about 0.1 joule with a minimum pulse rate of 100 to 1000 p/s when the beacon beamwidth (determined by atmospheric effects) is 10^{-4} radian. As an example, if the space vehicle optics disturbance frequency is 10 Hz (it will be difficult to isolate the optical system from coarse attitude control systems at frequencies below 10 Hz), then the necessary servo bandwidth is 160 Hz to achieve 10^{-6} radian pointing precision. Under these conditions, 10 beacon pulses/Hz or 1600 beacon pulses/s are needed (which is beyond the present art for pulsed lasers). Approximately 15 dB signal-to-noise ratio is required in the beacon tracking servo loop independent of the space vehicle disturbing acceleration or servo bandwidth.

The beacon beamwidth can be reduced below 10^{-4} radian, perhaps to 10^{-5} radian, for a pulse beacon outside the Earth atmosphere. In this case, laser beacon feasibility becomes more attractive for tracking control at 1 AU range, although severe device problems still exist. It is concluded that an optical beacon for autotracking at a distance of 10 AU is not feasible with the present art.

3.3.4 Modulation and Detection

At a 0.5μ wavelength, direct detection with polarization shift modulation is the preferred mode for either a ground or orbiting Earth receiver. For a 10.6μ link, heterodyne detection with biorthogonal phase modulation is the preferred system. Pulse position modulation (PPM) offers potentially higher efficiency, but at a considerable increase in circuit complexity. Both techniques deserve further study and experimentation.

Heterodyne detection is chosen for a 10.6μ system primarily because of the high noise characteristic of far-infrared photoconductor detectors. Analysis shows that tens of milliwatts of local oscillator power permit operation of a 10.6μ link at or near the shot noise limit.

3.4 System Comparisons

3.4.1 Canonic Mission – Mars Orbiter

Parameters of a Mars orbiter are considered only to the extent that the orbital parameters affect the communications. Simple models are employed to estimate:

1. The fraction of time a Mars orbiter is occulted by Mars, which is important in determining under what conditions continuous communication is possible
2. The fraction of time Mars is within the beam of the Earth transmitter, which is important for noise considerations in an optical communication system
3. The magnitude and variation of Doppler shift, which is of particular importance for 10 micron heterodyne detection optical systems
4. Visibility conditions from a tracker satellite situated at a triangular libration point of the Earth–Moon system, which is important for navigation
5. Visibility periods of a Mars orbiter relative to a space probe approaching from Earth, also important in navigation
6. Payload considerations for a Mars mission, which is important in determining the weight that may be allocated to the communication system
7. Visibility conditions between a Mars landing vehicle and a Mars orbiter
8. Visibility of a Mars synchronous satellite from an Earth synchronous satellite, both of which relate to the question of maintaining continuous communication.

The principal conclusion of these investigations is that there are periods of two or three months, two or three times per year, when continuous communication is possible between an Earth synchronous satellite and a Mars synchronous satellite.

3.4.2 Performance of S-Band

Over the past decade more than five orders of magnitude improvement in deep space communication capability have been achieved, and nearly three orders of further improvement are planned in the Voyager system. This is illustrated in Table 6 where system parameters are given for Pioneer IV, Mariner II, Mariner IV, and Voyager. The last column of the table gives the signal-to-noise ratio at the receiver, relative to Mariner IV.

Further significant improvements in received signal-to-noise ratio will come from increased space vehicle ERP (effective radiated power) rather than from increased receiver aperture or lower noise receiving systems. Figure 10 indicates the transmitter power and antenna gain of the systems noted in Table 6. The solid lines in this figure give the power and antenna gain to achieve a given effective radiated power with minimum weight. There are three such lines corresponding to the use of solar cells in the vicinity of the Earth (1 AU), solar cells in the vicinity of Mars (1.7 AU), and reactor prime power which gives less weight than solar cells for all distances greater than 2 AU from the Sun.

The analysis leading to the minimum weight design is presented in Chapter 5, Section 2. It is shown that, as the ERP increases, the weight of the spacecraft communications (viz., prime power, power supply, transmitter, and antenna system) increases as $(\mathrm{ERP})^{3/8}$. Thus, to go from a 50 dBW ERP (Voyager) to 70 dBW would require an increase in weight by a factor of about 6. The minimum weight is shown as a function of ERP in Figure 11.

In Figure 12, the information rate is plotted as a function of range for ERP = 50, 60, 70, 80 dBW, assuming DSIF receiving parameters and an E/N_0 requirement of 10 dB. Although this latter assumption is about 4 dB poorer than what can be achieved with advanced modulation and coding techniques (see Chapter 1, Section 6), it allows for both losses in the transmitter and receiver and for some margin. It follows from Figure 12 that to achieve an information rate of 10^6 bits per second from 1 AU requires an ERP of 57 dBW. This could be achieved, for example, with the same 50-watt (17 dBW) tube as in Voyager and a 5.8 meter (19 ft) antenna, which appears well within the state of the art. To achieve 10^6 bits per second from 10 AU would require an ERP of 77 dBW, which could be achieved (see Figure 10) with a 500-watt transmitter (27 dBW) and an 18.2 meter (60 ft) antenna. This antenna is estimated to weigh 600 lb (see Figure 13); the weight of power, transmitter, and antenna is estimated at 1000 lb (Figure 11). Thus, it would appear that present microwave technology is sufficient to achieve 1 Mb/s from a distance of 1 AU, and that the achievement of 1 Mb/s from a distance of 10 AU is consistent with reasonable estimates of future space transmitters and antennas.

3.4.3 Performance of X-Band, K-Band, and Millimeter Wavelength

In Figure 14 the product of transmitting antenna gain and receiving antenna effective area is given as a function of frequency for fixed transmitting antenna weight and ground receiving antenna cost. The curves in Figure 14 are monotonic increasing, so that millimeter wavelengths would offer an advantage if there were no frequency-dependence of transmitter power, receiver noise, and atmospheric attenuation. Unfortunately, although the first may be approximately true, neither the second nor the third assumptions are applicable in the millimeter band.

In Table 7 the performance degradations (relative to a system at 2 GHz) caused by light rain are listed. In Table 8 the results of Figure 13 and Table 7 are combined to give the signal-to-noise ratio (and hence the information rate) on a relative decibel scale for various combinations of space antenna weight and ground antenna cost and for various frequencies in the microwave and millimeter bands, for a system designed to operate through periods of light rain (0.1 in/hr).

To convert the relative performance data in Table 8 to information rate H, it is necessary to assume a transmitter power P, a range R, and a performance measure of the modulation system E/N_0. For P = 100 watts, R = 1 AU, and $E/N_0 = 10$ [H is proportional to $(P/R^2, E/N_0]$, the 0 dB entry in the table corresponds to $2.5\,(10)^5$ bits/s. Thus,

Table 6

DEEP SPACE COMMUNICATION SYSTEMS

	f (GHz)	P_T (watts)	G_T (dB)	D_R (feet)	T (°K)	Δ* (dB)
Pioneer IV (1959)	0.96	0.27	2.5	85	1450	-51.4
Mariner II (1962)	0.96	3	19	85	250	-16.8
Mariner IV (1965)	2.29	10	24	85	55	0
Voyager (1973)	2.29	50	32	210	25	+26.4

$*\Delta = 10 \log \ (P_R/T)/(P_R/T)_{\text{Mariner IV}}$

Table 7

PERFORMANCE DEGRADATIONS CAUSED BY ATMOSPHERIC LOSS UNDER CONDITIONS OF 0.1 IN/HR RAINFALL OR VERY DENSE CLOUD COVER

	2 GHz	8 GHz	16 GHz	35 GHz	94 GHz
Att (dB)	0	0.1	0.8	3.5	13.4
T_{atm} (°K)	0	7.2	24	130	285
T*	25	32.2	49	155	310
10 log T/25	0	1.1	2.9	7.9	11
Degradation (dB)	0	1.2	3.7	11.4	24.4

* System input noise temperature is assumed to be 25° K at all frequencies.

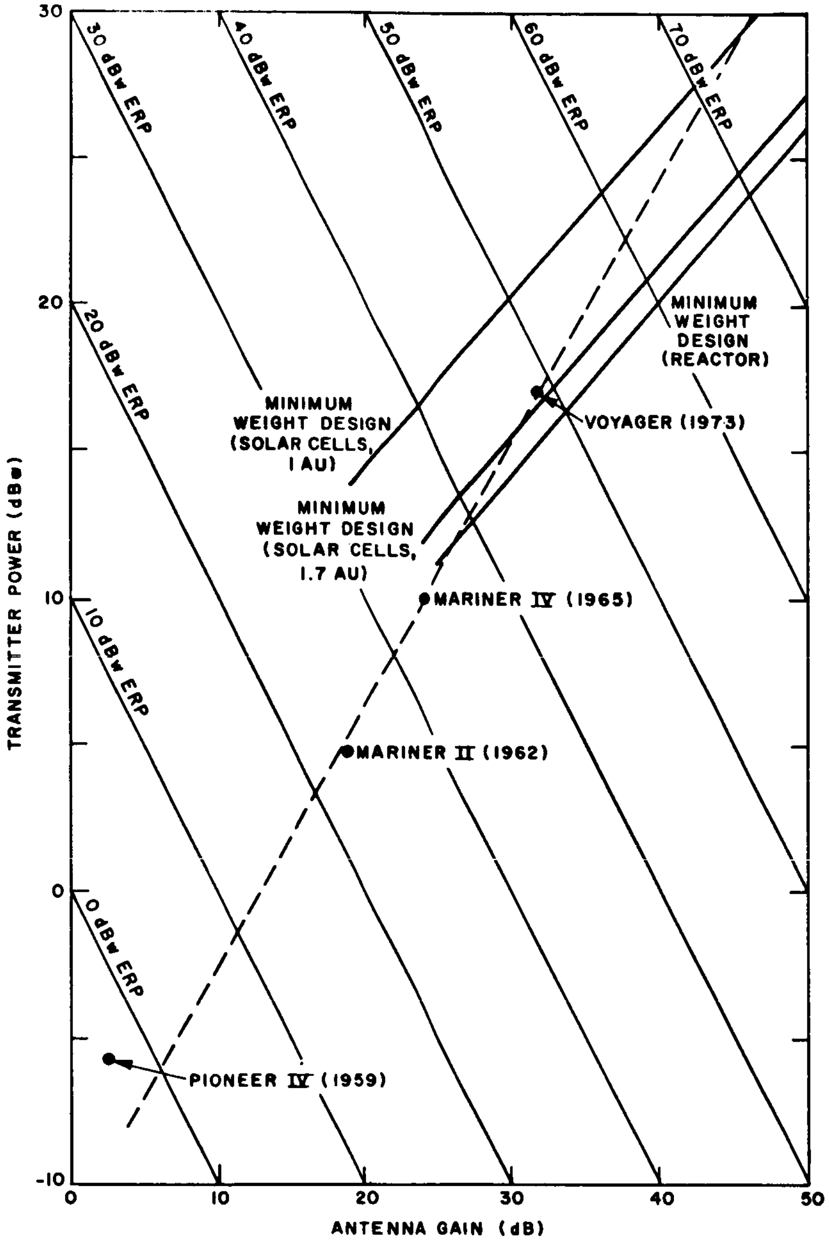


Figure 10. Effective radiated power of deep space communications systems

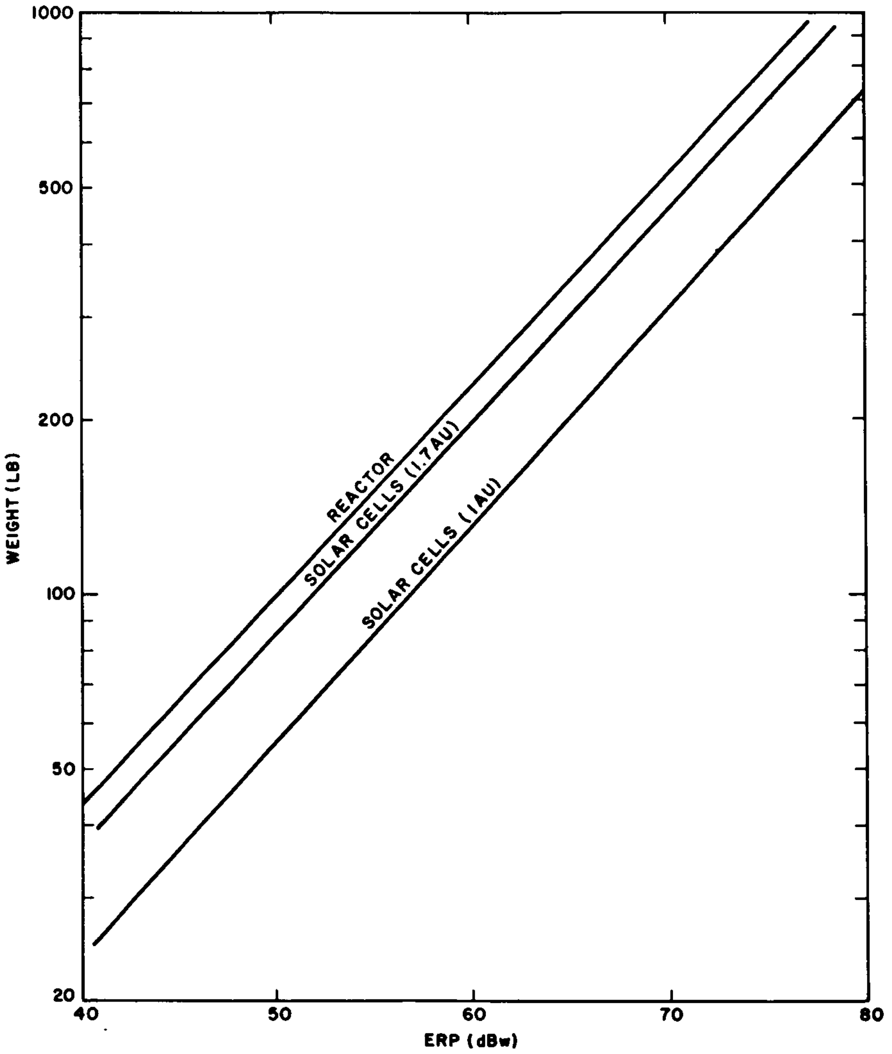


Figure 11. Weight required to achieve a given effective radiated power

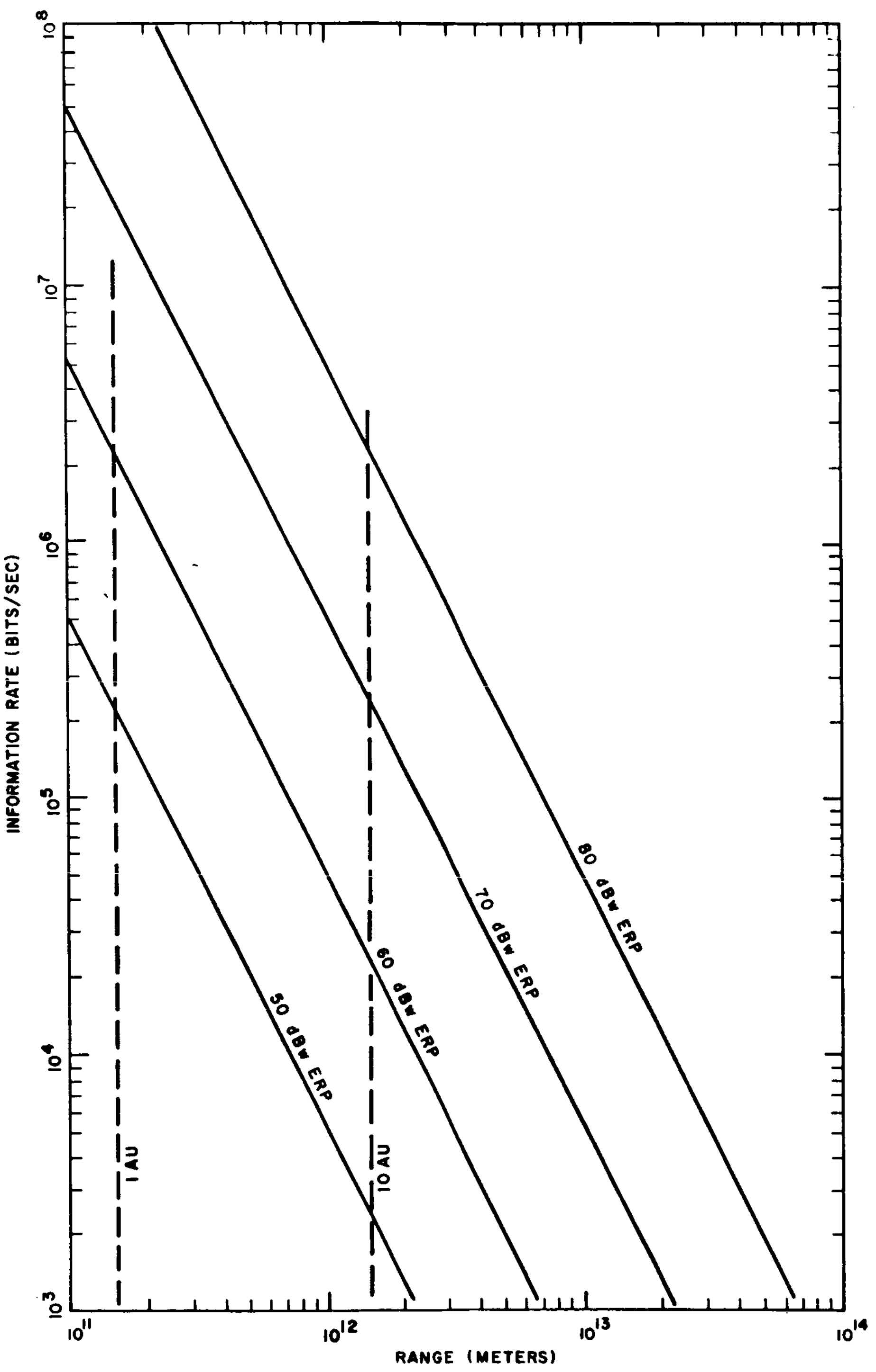


Figure 12. Information rate achievable with DSIF

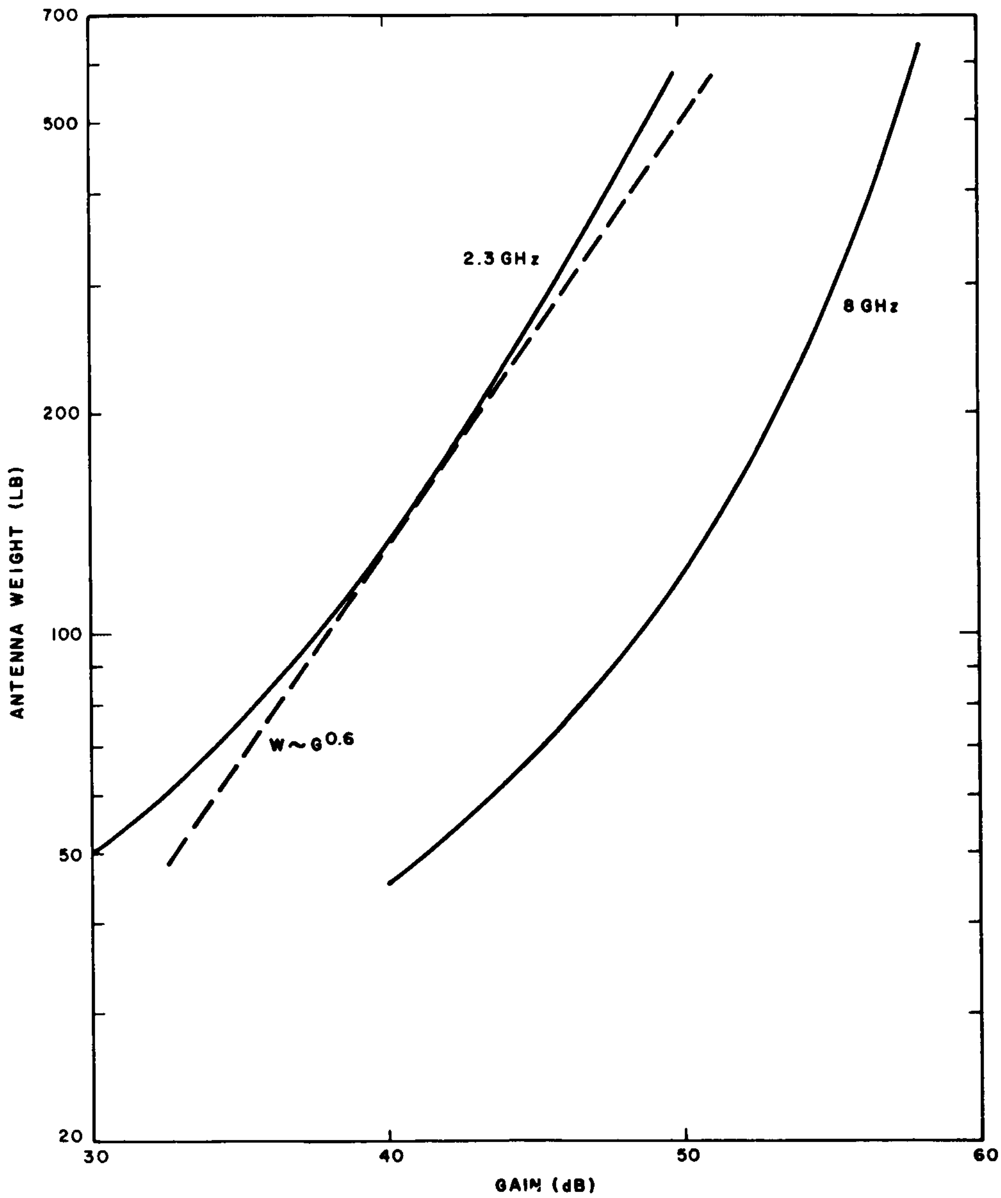


Figure 13. Space vehicle antenna weight required to achieve given gain

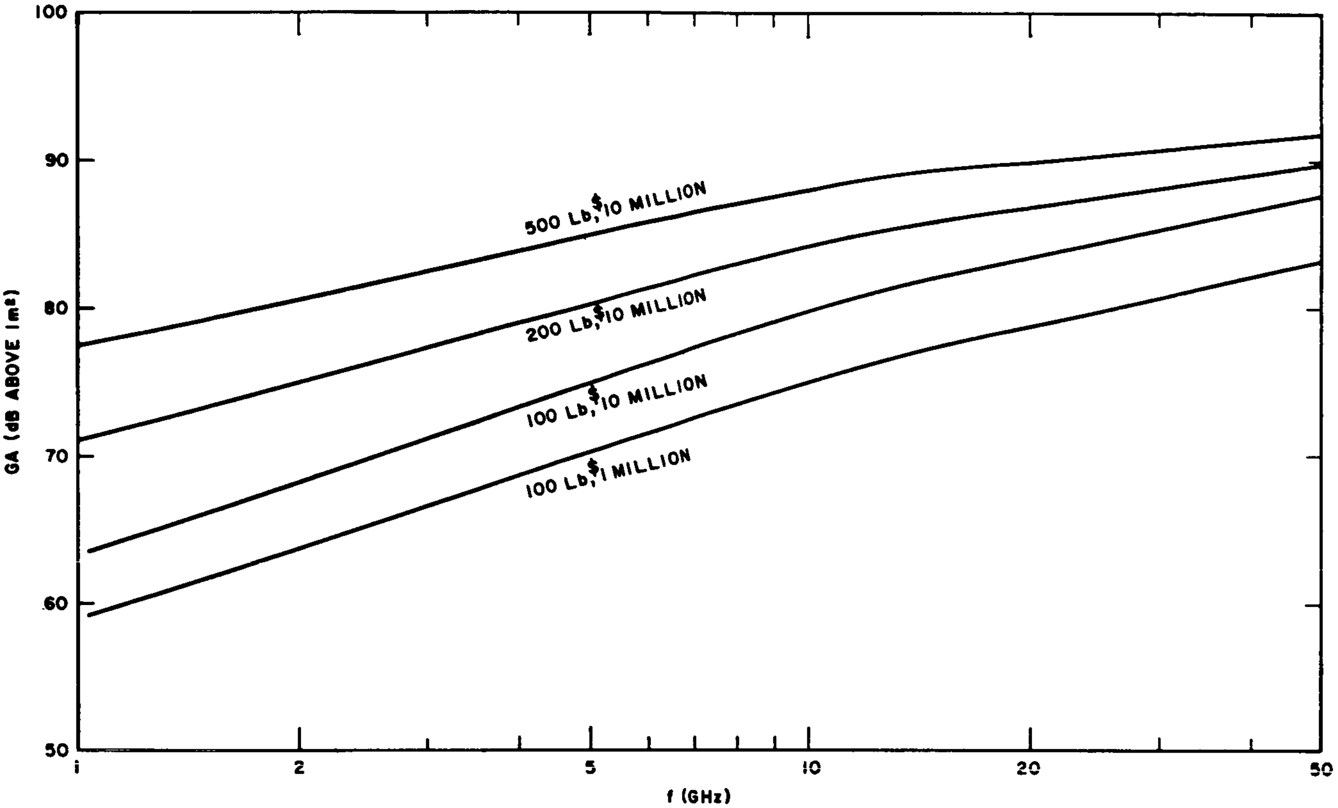


Figure 14. Frequency dependence of product of gain of fixed weight transmitting antenna and area of fixed cost receiving antenna

Table 8

RELATIVE SYSTEM PERFORMANCE (dB) DURING LIGHT RAINFALL (0.1 in/hr)

Space antenna weight (lb)	100	100	200	500
Ground antenna cost	$\$10^6$	$\$10^7$	$\$10^7$	$\$10^7$
f = 2 GHz	0	4	11	17
f = 8 GHz	9	13	18	23
f = 16 GHz	10	15	18	22
f = 35 GHz	6	11	13	16
f = 94 GHz	0	4	5	7

for example, the use of a 100 lb space antenna and a \$1 million ground antenna would achieve an information rate of $2(10)^6$ bits/s at 8 GHz (assuming again $P = 100$ watts, $R = 1$ AU, $E/N_0 = 10$).

It must be remembered that Table 8 includes only the margin required to guarantee operation of a system through light rainfall. If a "data-dump-on-command" philosophy is adopted to accommodate loss of communication during more serious weather conditions, the higher frequency systems must be capable of data rates higher than the 2 GHz system by a percentage consistent with the highest percent outage time expected during the mission.

Several interesting conclusions may be drawn from Table 8.

1. There is an appreciable advantage (6 to 9 dB) in going from 2 to 8 GHz.
2. The performance at 16 GHz is essentially the same as at 8 GHz under the assumed light rain conditions. Note, however, from Table 2 that there would be considerably more degradation at 16 GHz than at 8 GHz under heavy rain conditions, and that considerably more margin would be required at 16 GHz if operation during heavy rainfall were required.
3. The performance relative to that at 8 GHz degrades appreciably at the millimeter frequencies. Note, however, that for the lighter spacecraft antennas, the performance at 35 GHz is better than that at 2 GHz. This conclusion must be tempered by the extreme sensitivity to weather conditions and the current unavailability of space qualified millimeter tubes. It is generally true, however, that millimeter frequencies are relatively more attractive when there is a tight constraint on spacecraft weight.

3.4.4 Millimeter Systems With a Satellite Receiver

As noted in the previous section, if margins are provided which permit communication through light rainy weather, millimeter wavelengths are less attractive than S-band for communication from a deep space vehicle to an Earth receiver. Consequently, consideration is also given to a deep space millimeter communication system in which the receiving terminal is located on an Earth satellite rather than on the ground, with communication from the satellite to the ground via S-band. This, of course, permits the use of frequencies outside the atmospheric windows for transmission from the space vehicle to the Earth satellite.

In Figure 15 the satellite receiver antenna diameter required to achieve the same communication rate as a 64-meter (210 ft) S-band receiver is shown as a function of frequency for two cases.

1. Transmitter power divided by receiver noise temperature is the same at millimeter wavelengths as at S-band.
2. This ratio is 10 dB poorer at the millimeter wavelengths than at S-band.

In both cases the transmitting antenna gain is scaled to keep a constant weight of 200 lb (see Figure 16).

Under the optimistic assumption of Case 1, a 3.2-meter (10 ft) receiving antenna would be required at 100 GHz. Under the more realistic assumption of Case 2, the receiving antenna diameter is 10.0 meters. However, a 10-meter Earth satellite antenna, good at 100 GHz, is outside the range of presently contemplated design.

The above results indicate that a millimeter system with a satellite receiver would require extensive development efforts in the areas of space transmitters, low-noise space receivers, and high-gain (70 to 80 dB) space antennas just to equal the performance of an S-band system with the present DSIF receiver. The prospects are remote for obtaining performance at millimeter wavelengths appreciably better than at S-band.

3.4.5 Comparison of Ground Vs. Satellite Receiver for Optical Systems

The question of whether the receiver for a deep space optical communication system should be located on the ground or in an Earth satellite is considered in Chapter 5, Section 5. Factors affecting the siting of ground receivers are reviewed. Although considerable cloud coverage data are available, the data show considerable variability and are inadequate to determine quantities such as correlation of cloud cover at widely separated points and the distribution or duration of outages and time between outages. Gross average cloud data can serve only to pinpoint particular sites at which more extensive measurements (e.g., monitoring solar radiation) should be performed. However, even if such data are taken, the variability of past data suggests extreme caution in predicting what cloud coverage may be.

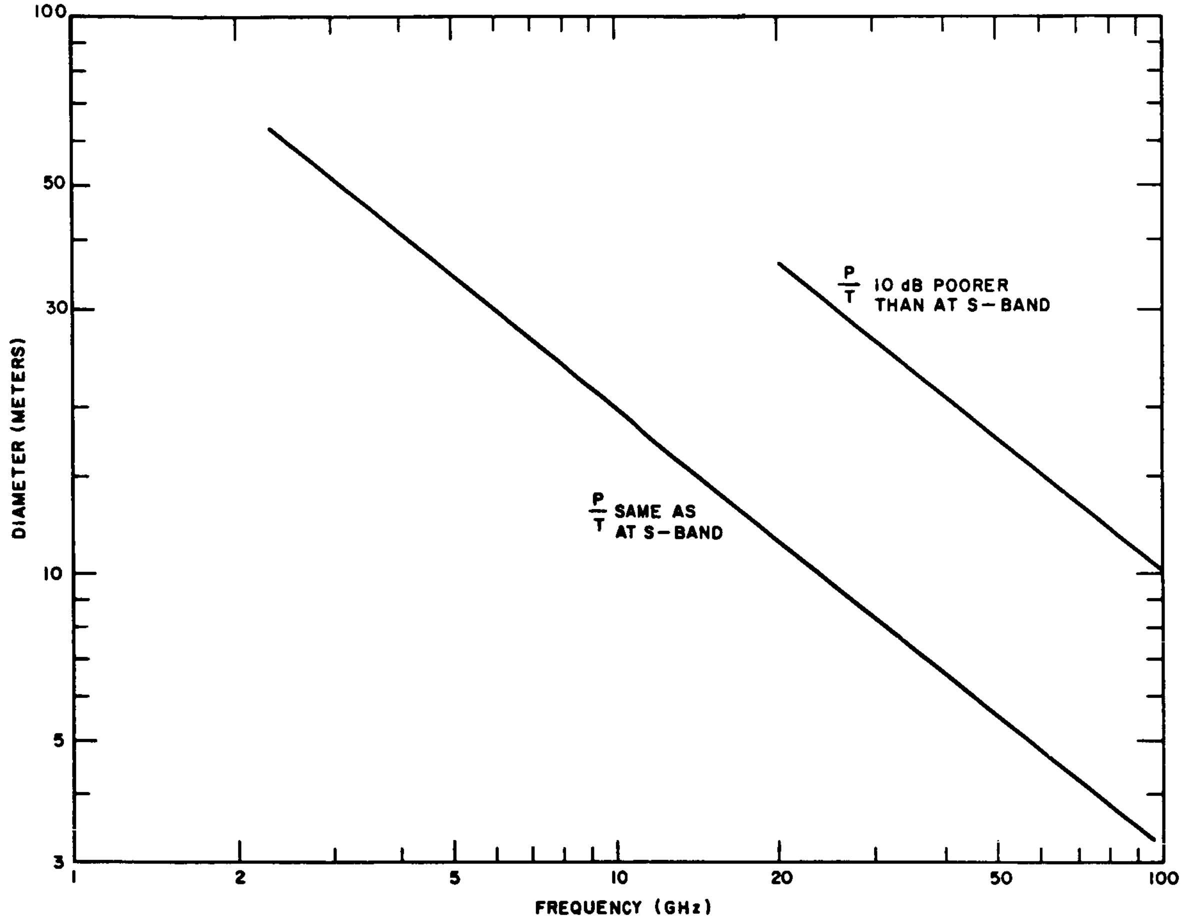


Figure 15. Satellite receiving antenna required to achieve same communication rate as S-band system with 64 m ground antenna

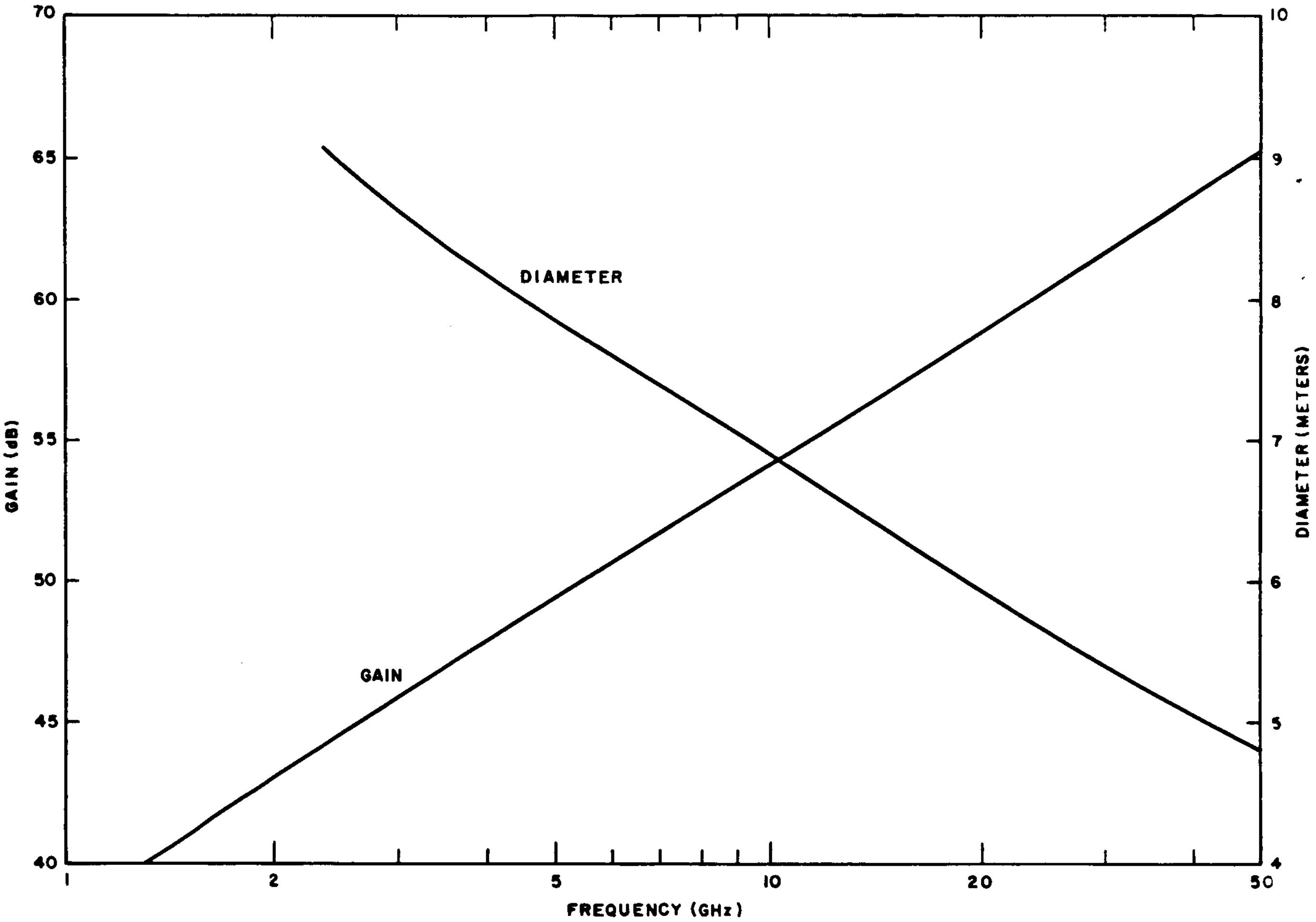


Figure 16. Gain and diameter of a 200 lb space vehicle antenna

Although spatial diversity may, in principle, improve reliability, there are problems in implementing a diversity system. It is necessary to code the beacons of the various ground stations. They must be separated in the wide-angle acquisition system of the space receiver, the strongest signal determined, and the transmitter locked to this signal. Although this is feasible in principle, it results in an appreciable increase in system complexity.

Diversity may counter extended periods of complete attenuation; it cannot counter amplitude fluctuations which are fast compared to the acquisition time but slow compared to the bit period. It is estimated in Chapter 5, Section 5.3, that the combination of standard atmospheric attenuation and the margin required for fluctuations results in a ground-based optical system requiring at least 12 dB more average signal power than that which would be calculated under free space conditions. This indicates, for example, that a satellite receiver need be only 1/4 the diameter of an Earth receiver for the same performance.

Another important advantage of the satellite receiver relative to the ground-based receiver is the reduced background noise (no day sky). For a direct detection optical communication system the sky noise in the optical filter bandwidth may exceed the signal power, in which case the PMT square law detector results in an appreciable performance degradation. For typical numbers, discussed in Chapter 5, Section 5.4, there is an 8 dB degradation in communication capacity caused by the background noise.

The beacon acquisition problem is also eased somewhat if a beacon is on a satellite rather than the Earth. The main advantage is that the beacon beamwidth is no longer limited by atmospheric effects and beamwidths narrower than 10^{-4} radians may be employed. Furthermore, for a beacon on an Earth synchronous satellite, there will be extended periods in which the Earth will not be within the field of view of the spacecraft acquisition receiver. Thus, acquisition need not be performed in the presence of Earthshine. This appreciably eases the beacon acquisition problem for a spacecraft in the vicinity of Mars. For a spacecraft at 10 AU, the acquisition of an optical beacon appears extremely difficult, even if the beacon is in a satellite (see Chapter 4, Section 4). Unlike the usual situation at microwaves, the power requirement on the beacon is more severe than that on the high data rate communications transmitter. This arises largely from the fact that the beacon, which is pointed on an open loop basis, must operate with a considerably broader beam than the narrow-beamwidth spacecraft transmitter.

Finally, as noted in Paragraph 3.4.1, a Mars synchronous satellite will be continuously visible from an Earth synchronous satellite for periods of several months. This is a particularly compelling argument for the use of a satellite receiver, since only a single satellite and a single ground station need be employed, with no concern for the problems of weather or handover.

Disadvantages of an Earth synchronous satellite for optical reception must also be considered. The acquisition beacon in the relay satellite must be open-loop pointed with an accuracy of 10^{-4} to 10^{-5} radian. This is not easily done with a gimbaled beacon.

The original cost of a relay satellite receiving terminal will be considerably greater than that of even several ground-based receivers capable of appropriately higher gain. The precise economic balance between ground-based and Earth synchronous satellite terminal systems cannot be established on the basis of our present knowledge and understanding of atmospheric effects at 10.6 microns. In the visible frequency range, more information exists and there is no doubt that a satellite relay will be cheaper if near full time communication capability is a requirement.

It is not unrealistic to expect the atmosphere to be far more friendly at 10.6 microns than it is in the visible frequency range, but for the moment at least it is not realistic to assume a system in which reliable propagation through the atmosphere is required. The following comparison between optical and microwave system performance will assume that an Earth synchronous relay satellite is used at infrared and optical frequencies.

3.4.6 Comparison of Optical and Microwave System Performance

A comparison of the relative performance of optical systems with a 2 GHz microwave system is made in Chapter 5, Section 6. This comparison is summarized in Table 9. The assumptions are listed in Table 9A and discussed below.

Heterodyne detection is considered at 10.6 microns, and direct detection at 0.53 micron. The overall efficiency (including ballast and power supply) of a high power, single mode, sealed CO_2 laser system is taken to be 8 percent. The overall efficiency of a Nd:YAG laser with second-harmonic generation ($\lambda = 0.53$ micron), considered to be the best candidate in the visible region, is taken to be 0.3 percent. The -7 and -21 dB entries in the first row of Table 9 are then the efficiencies of the laser systems relative to a 40 percent efficient microwave system. The comparison is thus made on the basis of constant prime power (in the 1 to 5 kW range) which is tantamount to constant weight. If the comparison were made on the basis of constant dissipated power, the penalties would be -9 and -23 dB. If the thermal problem is controlling, this latter comparison is more meaningful.

A 1 meter telescope, weighing approximately 1000 lb, is assumed for the visible transmitter. The gain advantage of the optical systems is then determined by considering the gain of a microwave antenna for the same weight (see Figure 17). The entries in the second row of Table 9 give these gain advantages. (The 1000 lb S-band antenna has a diameter of 72 ft and gain of 51 dB.) If the comparison

Table 9

PERFORMANCE OF OPTICAL SYSTEMS RELATIVE TO A 2.3 GHZ MICROWAVE SYSTEM

(All Entries in dB)

	10.6 Micron Heterodyne	0.53 Micron Direct Detection
Power	−7	−21
Transmitting gain	+60	+83
Receiving area	−33	−33
Noise temperature	−17	−30
Receiver losses	−4	−10
E/N_0	0	−2
Net advantage	−1	−13

Table 9A

SUMMARY OF THE ASSUMPTIONS MADE IN DERIVING THE NUMBERS FOR TABLE 9

	2.3 GHz	10.6 Microns	0.53 Micron
Efficiency (%)	About 80 dBW, ERP (see Figure 12) 40 (About 1 kW output)	8	0.3
Transmitting gain (dB) (1000 lb antenna or telescope)	51 (Diameter=72 ft)	111 (Diameter=1.4m)	134 (Diameter=1m)
Receiving Area			
Diameter (meters)	64	1.4	1.4
Location	Earth	Relay satellite	Relay satellite
Noise temperature (°K)	25	1350 (Quantum limit)	27,000 (Quantum limit)
Receiver losses	≪1 dB		
Quantum efficiency		0.5	0.2
Overall optical efficiency		0.8	0.5
Modulation	Coherent biorthogonal	Coherent biorthogonal	Incoherent polarization shift

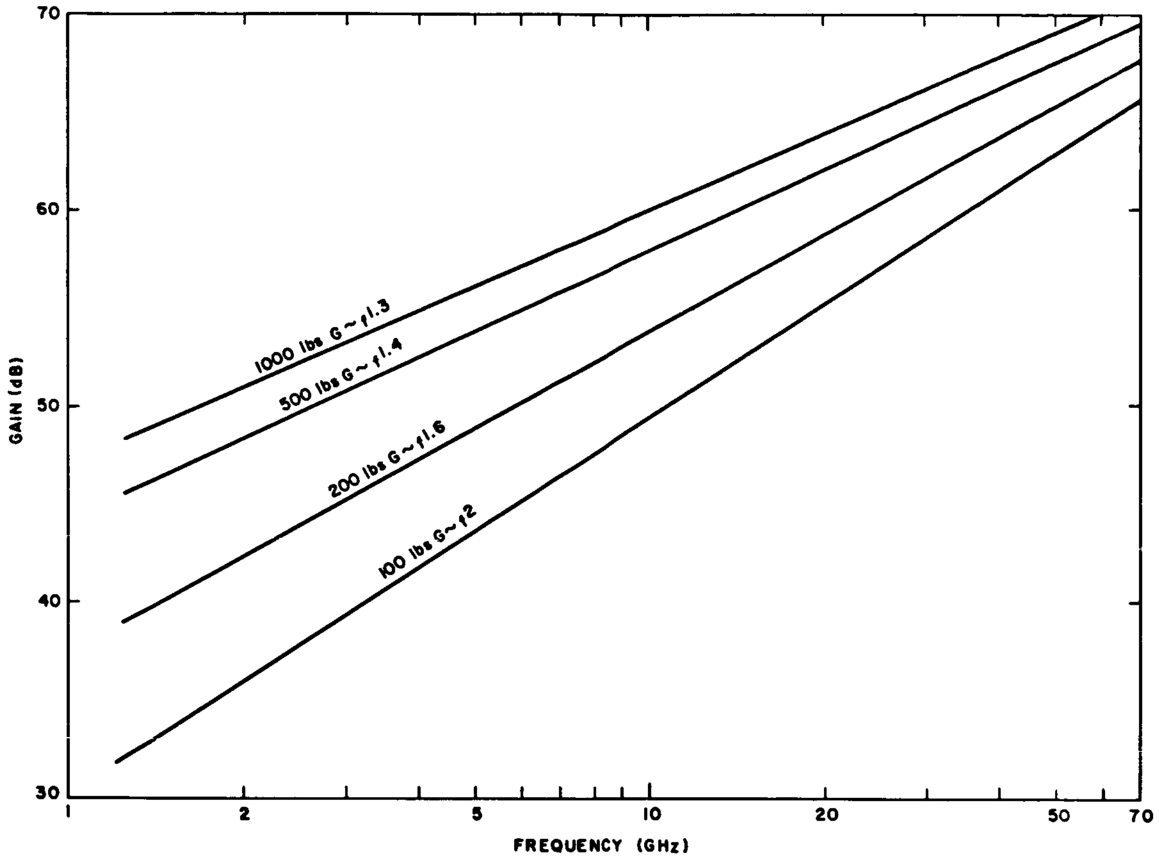


Figure 17. Gain vs. frequency of space antennas (constant weight)

were made at lower weight, the gain advantage of the optical systems would be reduced (Figure 18). A 1.4 meter aperture-limited reflector is assumed to weigh 1000 lb for the 10.6 micron wavelength. This assumes that present-day technology used in the construction of telescopes that operate at visible wavelengths can be utilized in the design of infrared reflectors. The result should be a larger infrared telescope for the same weight (here taken to be 3 dB larger in area).

The receiving effective area comparison in Table 9 is on the basis of a 1.4 meter optical telescope (in an Earth satellite) at both $\lambda = 0.53\mu$ and 10.6μ, and the 64 meter (210 foot) Goldstone dish at 2.3 GHz. The 1.4 meter telescope would be diffraction limited at 10.6 microns, but need not be diffraction limited at 0.5 micron where direct detection is employed.

The comparison of noise temperatures in Table 9 assumes that the optical systems have an effective noise temperature given by $h\nu/k$ (the quantum limit), as compared to a system noise temperature of 25°K at 2.3 GHz. The receiver losses in the optical system include the quantum efficiency of the detector (0.5 at 10.6μ and 0.2 at 0.53 micron), filter and polarization losses in the direct-detection system, and imperfect matching of signal and local oscillator in the heterodyne system. The direct-detection system cannot employ coherent demodulation, and has an additional 2 dB penalty in "detection efficiency."

The numbers in Table 9 are based on conservative optimism about the continuing development of both microwave and optical techniques and devices. The 2.3 GHz system to which they are compared is largely based on existing techniques, though further development of space transmitters and erectable space antennas would be required here, too. Also, it is assumed that a balanced system would utilize synchronous satellites whose launched cost does not differ greatly from that of the space probe. This assumption does not provide a completely satisfactory comparison between optical and microwave systems since the optical system requires a synchronous satellite and the microwave system does not. Of course, the microwave terminal antenna exists today.

A cost-effective comparison would require a study of Earth terminal development and maintenance costs that is beyond the scope of this report. The total cost of final construction and maintenance of a world-encompassing net of microwave Earth terminals and communications systems must be compared with the cost of development and maintenance of one or more (depending on visibility, reliability, and life) Earth synchronous relay satellites and their associated Earth terminals. Antenna costs are a significant part of Earth terminal costs, but weigh heavily in the entire system costs only in the upper range of total aperture sizes.

A factor in such a cost study is the practical necessity of including emergency means for communication link recovery. Present-day systems include an S-band command link utilizing omnidirectional satellite antennas, but other reasonable link restoral techniques are conceivable. Where satellite high data rate communication equipment can also be used for link restoral, the communication cost will be influenced.

With the assumptions listed in Table 9A, the infrared heterodyne system achieves nearly the same performance as the microwave system, whereas the visible system is more limited. It can be concluded that optical communication systems can achieve high capacity communication from deep space, but for the canonical mission assumed in this comparison, a microwave system can achieve similar or better performance more readily. It should also be noted that, although the 10.6 micron system is (according to Table 9) 12 dB better than the 0.53 micron system, this presumes the development of appropriate tracking techniques for heterodyne receivers, high-speed detectors, and materials capable of providing modulation of high power signals with low loss and low power consumption. Also not reflected in these numbers are the more difficult problems of acquisition and tracking necessary to establish and maintain the optical communication links, as discussed in Chapter 3, Section 4, and Chapter 4, Section 3. It may not even be possible to maintain lock of such an optical transmitter at distances greater than 1 AU.

An effort was made to estimate the growth which might be possible for the three systems: 2.3 GHz, 0.53μ, and 10.6μ. The values in Table 9 were examined, and the magnitude of the improvements which are both physically possible and technologically conceivable were estimated and entered in Table 10, again in dB. It is emphasized that these numbers are not exact. They are subject to the uncertainties in the experience, imagination, and engineering intuition of the individuals whose joint contemplation developed them.

The efficiency of the 2.3 GHz transmitter power amplifiers has been taken to be 40 percent; however, programs are under way to improve that capability and it is not unreasonable to expect as much as 50 percent. Single-mode, sealed CO_2 lasers may achieve higher than an 8 percent overall efficiency through optimization of laser parameters and other special techniques being investigated. A doubling of efficiency is not likely, but an increase of 2 dB may be possible. The low efficiency of signal generation at 0.53μ results largely from the inefficient spectral match between the pump lamp and the Nd:YAG crystal. Matching of the radiation spectrum of an efficient light source to the crystal could conceivably increase the efficiency by as much as 11 dB and still not approach the limit on efficiency set by population inversion. (See Chapter 3, Section 1.)

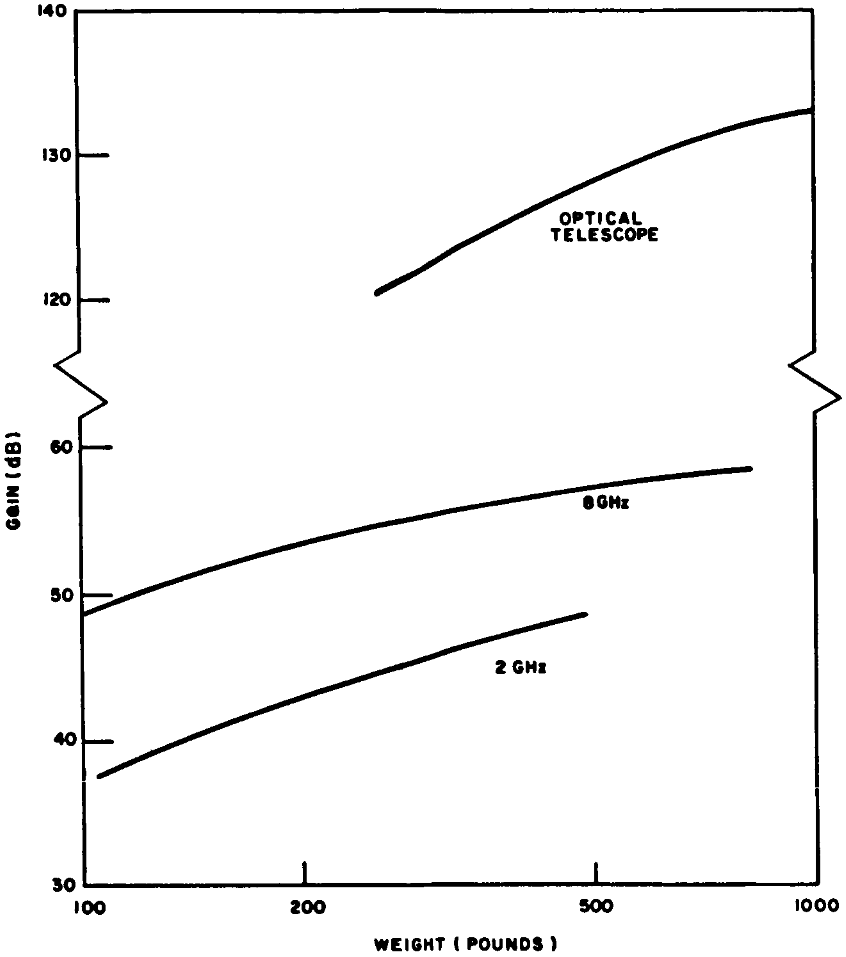


Figure 18. Comparison of the gain of space telescopes and microwave antennas

Table 10

POSSIBLE GROWTH IN DB OVER CANONICAL SYSTEMS ASSUMED IN TABLE 9

	2.3 GHz	10.6μ	0.53μ
Power	+1	+2	+11
Transmitting gain	+14	+9	0
Receiving area	–	+9	+9
Noise temperature	+2	0	0
Receiver losses	0	0	+3
E/N_0	+2	+2	+7
Net growth	+19	+22	+30

Chapter 1, Section 3 discussed inflated structure spacecraft microwave-antennas but did not include them in the parametric evaluation due to the development problems known to exist in this area. Some aerospace antenna developers would take serious exception to this neglect, and the future may prove them right. Even inflatable structures have minimum mass limitations, but it is not inconceivable that the empirical limitations on weight and surface accuracy assumed in Table 1 could be bettered, and that a 300 ft inflated structure, mesh reflector antenna could weigh as little as 1000 lb. This could make possible a 14 dB increase in gain over the assumed 72 ft antenna.

At 10.6μ, it does not seem unreasonable to consider 1000 lb transmitters as large as 4 meters in diameter. Although temperature gradients will continue to be a tough space problem, much improvement may be possible in structural efficiency considering the weightlessness of the space environment. Here we are presuming the development of a technology which is novel but entirely feasible. In a weightless low thermal flux (several AU distance from the Sun) environment, the reflector can have a very large ratio of diameter to thickness. However, current technology for perparing optical surfaces which are diffraction-limited at 10.6μ involves grinding, polishing, and testing in a gravitational field, and this requires some reasonable thickness of the blank. Means for final figuring in a weightless or quasi-weightless condition must be developed.

At 0.53μ, a 1 meter aperture-limited reflector is already extremely demanding. The above observations also apply here, but gains to be made against modern telescope techniques are far less hopeful. Furthermore, the directivity of a 1 meter reflector at 0.53μ already taxes autotracking and pointing control capabilities. All in all, increase of transmitter antenna gain at 0.53μ beyond that achievable by a 1 meter telescope seems unlikely.

There is no doubt that one can increase the receiver area at 2.3 GHz indefinitely, though at appropriately large cost. Since the cost of the ground system is a controlling item, it seems inappropriate to indicate growth margin. The constraint placed on receiving aperture for optical systems, however, is mass, since it is assumed that an Earth synchronous satellite will be used. It is appropriate, then, to consider a growth margin not unlike that for the 10.6μ transmitter antenna. Again, the 4 meter aperture will be aperture limited (for coherent detection) at 10.6μ but not at 0.53μ.

Physical limitations on the noise temperature for the microwave receiver system are set by the sky noise (about 5°K) and the maser noise (about 5°K). Practical limitations involve side-lobe reception of noise from the antenna environment and loss in the microwave transmission system. It is conceivable that a receiving system could be built having a noise characteristic as low as 15°or 16° K. The noise assumed for the optical systems is set by quantum noise, and it cannot be improved.

Table 10A

SUMMARY OF THE ASSUMPTIONS MADE IN DERIVING THE NUMBERS FOR TABLE 10

	2.3 GHz	10.6μ	0.53μ
Power	Amplifier efficiency improvement from 40 to 50%	Laser efficiency improvement from 8 to 12%	Laser efficiency improvement from 0.3 to 4.0%
Transmitting gain	Establishment of 1000 lb, 300 ft inflatable structure antenna	Establishment of 1000 lb, 4 m, aperture limited telescope	Tracking problem limiting
Receiving area	Cost limited	Establishment of 1000 lb, 4 m, aperture limited telescope	Establishment of 1000 lb, 4 m, non-aperture limited telescope
Noise temperature	Reduction of equivalent background noise from 25°to 16°K	Quantum limited	Quantum limited
Receiver losses	Already negligible	Losses already low	Improved filters and photoemissive materials
E/N_0	Improved coding	Improved coding	Introduction of efficient pulse position modulation

Receiver losses in a microwave system are small indeed and no appreciable help is to be found here. At 10.6μ no help is to be found short of finding detectors with quantum efficiency higher than 50 percent. This is already very good. At 0.53μ it is possible that filter losses could be slightly reduced. Also, it is not unlikely that new low dark current photoemissive materials will be found with higher quantum efficiency, and such development work is now active. It seems reasonable to allow for 3 dB improvement of these characteristics.

Improvement in E/N_0 is possible through better coding and detection techniques for the heterodyne systems, and introduction of efficient pulse position modulation for the non-coherent system.

It is apparent from the net growth figures in Table 10 that development of these systems depends significantly on the estimates of growth of the various technologies. The total range of possibilities suggests that 2.3 GHz and 10.6μ communication systems are comparable. Combining Tables 9 and 10 indicates that at present the situation appears to be just a little less hopeful at 0.53μ. It is at least possible that improved transmitter efficiency and enlargements in areas of an incoherent receiver may be more readily achieved than the technological improvements suggested at 10.6μ and at 2.3 GHz; but transmitter autotracking in the visible range will continue to be very difficult, if possible at all, in deep space probes.

3.5 Recommendations for Research and Development of Space Communications

It would be a mistake to recommend any specific course of research without full insight into future space missions. The evaluation of the canonical deep space communication system and its growth potential provides at least some cause for judgment about the significance of individual research and development efforts, but cannot be the sole basis. For example, a canonical low-orbit-to-synchronous-satellite communication system evaluation could be carried out (using the same basic information and related criteria) and the conclusions would be different. Hence, no categorical conclusion or recommendation can be made based only on this report.

On the other hand, certain specific suggestions follow from the study.

1. In the optical frequency range 10.6 microns and 0.53 micron are optimum wavelengths; effort should be concentrated there because of existing devices.
2. Investigation of the frequency characteristics of the existing DSIF 210 ft antennas and DSIF weather characteristics between 4 and 10 GHz should be carried out.

The following paragraphs suggest items that require effort to firmly establish capabilities that are only putative now, and to explore most effectively the growth potential for optical communications.

3.5.1 Visible Wavelength Systems

By far the greatest gains to be made in the visible frequency range lie in the establishment of high efficiency lasers. Nd:YAG second harmonic generators offer the greatest hope through the design of pumping lamps whose spectral characteristics more closely match those of the upper level transitions in the crystal. If other visible frequency generators come along having efficiency in the 1 to 10 percent range, they will deserve similar attention.

The critical block to further growth at visible frequencies is the problem of acquiring and tracking the optics. Experimental demonstration of the ability to establish and hold satellite orientation, and to acquire and autotrack the transmitter optics with the necessary accuracy, is essential. Further study and analysis of autotracking control techniques and systems is also recommended. Here the problem is to find means for autotracking on a weak received signal in the presence of satellite onboard disturbances.

3.5.2 10.6 Micron System

Acquisition and autotracking will be problems at 10.6 microns also, but not nearly as critical as in the visible range. At least theoretically there is room for aperture growth.

Communication systems of 10.6 microns will require components that have not been demonstrated yet, even as laboratory entities. Heterodyne detection in a high gain receiver system; Doppler tracking of a 10.6 micron heterodyne detector to accommodate satellite range-rate variations; a low loss, high data rate, low power consumption modulation system; and long life, reliable laser systems all remain to be realized. It is certainly recommended that they be developed.

By far the greatest growth potential at this frequency lies in the development of techniques for fabricating and figuring large lightweight reflectors. An increase from 1.4 to 2 meters diameter without increase in weight (1000 lb) would improve the 10.6 micron canonical deep space communication system by 6 dB (see Table 9).

Finally, if more information on the effects of weather and atmosphere at 10.6 microns were available it is conceivable that effective use could be made of Earth based receiving terminals at this wavelength. A coherent program of measurements and analysis is recommended.

3.5.3 Microwave Systems

A satellite transmitter amplifier and a deployable space antenna have been assumed in the 2.3 GHz canonical system that are extrapolations of existing devices. These also ought to be proven in. It is recommended, however, that the possibility of operating the present 210 ft DSIF antenna at higher microwave frequencies be explored to determine the best direction for further development of other system components.

Growth potential here lies in the development of very large, lightweight (inflatable structure) space antennas and techniques for directing them.

3.6 Tracking and Navigation Studies

The deep space navigation studies, involving various kinds of observations, were undertaken in parallel with the communications-oriented work reported in Chapters 1 to 5. Two combinations of tracking data were compared: one consisted of range and range rate measurements in the appropriate rf spectrum, the other was augmented by angle measurements between the optical line of sight (to the space probe or Earth satellite, as the case may be) and neighboring stars. The same model missions, i.e., a Mars flyby and an intragalactic probe, were considered specific exercises.

The purpose of these navigation studies was to model the error propagation in various mission phases with an eye toward evaluating the merits of different kinds of data, particularly optical angle measurements for trajectory determination. In approaching the individual error propagation studies, the simplest conceivable dynamical and statistical models were examined first to identify the essential factors for each situation in a qualitative way. In most cases these models involved planar motion with a very rudimentary representation of orbits. Some of the subsequent refinements, which could be justified within the present study, led to three-dimensional formulations and numerical integration of the vehicle motion rather than approximation by conic sections.

Four distinct tracking problems are treated in Chapter 6.

1. The steady-state navigation along Earth-Mars transfer trajectories
2. Tracking operations during the initial phase of a Mars mission, involving tracking relays in near-Earth orbits
3. Tracking operations during the terminal phase of a Mars mission, involving a Mars orbiter
4. Steady-state tracking of an intragalactic probe.

In the first example, an existing three-dimensional simulation was used, which generates the trajectory and its transition matrix by numerical integration. Random and bias errors were considered in the measurements, which consisted of range, range-rate, and optical angles. It turned out that optical angle measurements with an rms error of about 1 to 2 sec of arc, as obtainable outside the atmosphere from a near-Earth satellite or the space probe, will considerably accelerate the trajectory refinement after transients. The latter could derive from injection maneuvers or midcourse corrections.

The second study represents a closer look at the near-Earth phase of a Mars mission. This involves the use of several synchronous tracking relays or stations at the libration points to yield a wide base line for triangulation and trilateration. Again, the use of optical angle measurements within 1 to 2 sec proves beneficial to rapid orbit refinement. In fact, it is equivalent to DSIF-type range data taken from the libration points. This feature could be demonstrated with a simplified mathematical model, which was restricted to two dimensions, and straight line approximations of the probe trajectory. The significance of this tracking capability during the initial phase of an interplanetary flight will depend on the particular mission involved.

In the third example, two-dimensional conic sections were used to represent the motions of a Mars orbiter and a passing space probe as they interact during flyby. The tracking data included those taken from near-Earth stations and directly between the two vehicles. The availability of the Mars orbiter as a tracking reference for the space probe offers a quick-response capability after sudden increases of trajectory uncertainty from thrust maneuvers. This predominant feature of the flyby situation is enhanced only in a secondary way by the availability of optical angle measurements.

Finally, the intragalactic trajectories were simulated by numerical integration and, as in the Martian mission, the addition of optical angles to typical range and range-rate measurements was found to shorten the settling time of the ephemeris significantly.

It should be noted that the precision of optical angles assumed in most examples implies a tracking telescope located outside the atmosphere; i.e., on a 24-hour satellite, on a station at the libration points, or in the space probe. The rms angle error of 1 to 2 sec would become about 15 sec if transmission through the atmosphere were assumed. This obliterates the accelerated trajectory convergence noted with optical tracking data in the above exercises.

Several ways of refining the navigation studies and rendering their results more reliable come to mind. Most conspicuous is the correlation actually found in the measurement noise and the presence of bias errors other than those due to instrumentation, viz., the inaccuracies of terrestrial constants (including station location errors of ground trackers) and of astrophysical constants, and the position errors encountered with tracking stations in near-Earth orbits. These effects are found in most realistic tracking situations. They require a modification of the filter formulas and impose an upper bound on the data rates that can be used to advantage. Both aspects imply a considerable extension of the error propagation studies. An effort of this kind would be necessary to establish the maximum ephemeris accuracies achievable with the most precise tracking instruments currently available, yielding rms errors about 10 meters in range and 2mm/s in range rate* over interplanetary distances.

Another area for further work lies in the modeling of autonomous navigation for deep space probes as required by most missions involving complicated terminal maneuvers such as the dispatch and retrieval of an excursion module. The success of terminal operations in these missions may depend largely on a quick response to anomalies in the flight path and, in case of equipment failure, switching between alternate tracking modes (e.g., sighting of an orbiter, surface land marks, or the stars). Timely execution of such maneuvers requires autonomy of the space probe.

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*Note, for example, G. W. Null, M. J. Gordon, and D. A. Tito, The Mariner IV Flight Path and its Determination from Tracking Data, NASA Technical Report 32-1108, Jet Propulsion Laboratory (August 1, 1967).

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