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Technical Report 32-1392

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Preface

The work described in this report was performed by the Telecommunications Division of the Jet Propulsion Laboratory.

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Abstract

The information data rate of deep space communication links used for spacecraft-to-earth purposes is always severely limited by the size and power capacity of the spacecraft itself. Present deep space communication links, utilizing S-band frequencies, have been improved to so high an efficiency that the information data rates obtainable cannot be increased significantly without attendant increases in spacecraft size. One solution to the problem of obtaining higher data rates is to operate the data link at frequencies higher than S-band. This report considers the operation of a reliable deep space communication link at such frequencies in the presence of weather disturbances, and presents a comparison of five potential systems: two microwave (X-band and mm-band) and three laser bands (10 μm, 4 μm, and near visible). The advantages and disadvantages of each of these systems are discussed, and recommendations for future work in these areas are presented.

A Study of Weather-Dependent Data Links for Deep Space Applications

I. Introduction

This report covers an investigation of several deep-space-to-earth communication links whose characteristics are quite different from those currently employed. The links considered are weather-dependent; i.e., they are characterized by bulk data storage in the spacecraft and command playback to the earth's surface via a weather-dependent downlink. The technology of bulk data storage is not discussed at length since photographic techniques have been successfully used in space with both the *Mariner* and *Lunar Orbiter* spacecraft. The problems of solar-radiation shielding, chemical storage, and others are engineering rather than fundamental problems.

It is worthwhile to make a comparison of the data dump type communication links with the existing interplanetary S-band communications technique. Before presenting this comparison, it is worth pointing out a comparative analogy in the history of transportation. The gasoline-powered automobile is, in many ways, a perfect device for a wide variety of functions. Its physical size, configuration, and performance have remained grossly unchanged for 30 yr, despite the concentrated efforts of one of the largest engineering groups in civilization. The automobile is an essentially perfect, general-purpose, all-weather device that will probably not be replaced for many generations (if ever), and will change form only slightly (e.g., electric rather than gasoline power).

Investigations performed early in this century clearly showed the airplane to be an inherently weather-dependent, unreliable, special purpose, costly, and dangerous conveyance. Most of these disadvantages still exist. However, airplanes have proven to be most useful in applications for which automobiles, trains, and steamships are inefficient. The aircraft industry has not yet found simple solutions to weather-dependency and reliability; rather, a variety of partial solutions are used.

As the automobile relates to transportation, S-band (2300 MHz) is an almost perfect frequency band for interplanetary communications. The noise spectral density is minimized in this band; the systems are virtually independent of weather; and, for modest data rates, the antenna sizes are reasonable. In principle, an S-band system can be built for very high data rates (e.g.,

10^6 bits/s from Mars), much the same as a 200–300 mph automobile can be built. However, the attendant costs (Ref. 1) suggest that other approaches should be at least investigated. The research may eventually result in a more cost-effective system. The tentative conclusions of this study are that an S-band system and a special-purpose, high-frequency system might both exist together on an interplanetary mission, as by comparison, the automobile and airplane exist for transportation.

II. Description of Comparisons

A. Basis for Choosing Five Weather-Dependent Frequencies

Spacecraft needs have resulted in the development of two types of S-band microwave data links, both weather-independent. These are the high-gain link, employing a directional spacecraft antenna, and the ultrareliable, omnidirectional telemetry and command link. By 1980, the pressure for greater data rates may bring about an additional type of link that accepts a somewhat greater risk of interruption. This link would attain greater average data rates without impractical increases in power and spacecraft-antenna apertures.

One approach to greater data rates is an extrapolation of S-band technology. This method would use larger spacecraft antennas, resulting in increased mission risk, and larger/arrayed ground antennas at increased cost. Another approach, investigated in connection with this study, is to change to a higher frequency for the increased antenna gain. Unfortunately, all frequencies that are significantly above S-band are weather-dependent. Five of these weather-dependent bands were selected in order to evaluate the risks, gains, and trade-offs. Bit-rate performance was chosen in order to be independent of frequency. For this reason, the equipment design had to be such that a specified, common communications capability could be provided. Since equipment design is susceptible to research and development, if potential and financial support are sufficient, and the equipment itself is also susceptible to technological breakthrough, this study is aimed at the performance requirements and estimates of the state of the art.

The first band chosen is X-band, at a frequency of 8.45 GHz, or a wavelength of 3.55 cm. This frequency is representative of the highest that satisfies three conditions. First, the link will be seriously degraded only by heavy precipitation. Ordinary clouds, light precipitation, or high humidity will only slightly degrade this link. Second, the existing NASA/JPL 210-ft antenna is usable with only a slight loss of gain from surface imperfection (Refs. 2 and 3). Third, spacecraft antenna pointing can probably be accomplished with relative ease. These three conditions represent a breakpoint, or discontinuity in communication capability, as a function of frequency. A system using a frequency much higher than this breakpoint (i.e., 15 GHz through visible light) will not be competitive unless it has spectacular communication capabilities. The system capability will have to compensate for: (1) sensitive dependence on weather, (2) existing unsuitable antennas, (3) existing tracking stations not being situated in dry, high-altitude sites, and (4) significant spacecraft and mission changes.

The second weather-dependent frequency to be considered is 90 GHz, or a wavelength of 3.3 mm. This choice was made because the frequency is representative of a second kind of breakpoint. Namely, it is the highest frequency to satisfy all of the following: (1) The signal is not appreciably absorbed by moderately dry air. (2) Reception is not seriously degraded by turbulent air, scattered sunlight from the target planet, or by daylight sky. (3) Thermal noise dominates over quantum noise. (4) Much of the necessary hardware is already developed.

Beyond the millimeter and submillimeter bands lie the laser wavelengths. The third choice for comparison is a band near 10 μm, which includes the principal lines in the oscillation spectrum of the carbon dioxide (CO_2) laser (and isotopic modifications). This band will be sensitive to seeing conditions caused by turbulent nonisothermal air because the randomness in the wavefront degrades the types of optical receiver that effectively discriminate against sky and planetary backgrounds. Nevertheless, there are compelling reasons for including this band. First, the power-conversion efficiency of the CO_2 laser is 10–15% (Ref. 4). This efficiency is higher than that of any other coherent source of wavelengths shorter than a few millimeters. The CO_2 laser is not plagued with heat-dissipation problems that threaten reliability and the useful lifetime of many other high-power laser types. The antenna gain attainable with a spacecraft telescope of reasonable size is very high. This requires special spacecraft pointing equipment, but the accuracies are probably not in excess of values consistent with reliable pointing. The atmospheric window from about 10–11½ μm is exceedingly transparent. Finally, there is a photoconductive detector—copper-doped germanium cooled by liquid helium—that has good quantum efficiency (carriers per photon). The detector has a sufficiently short response time to allow a wide choice of intermediate frequencies in the receiver system, and information bandwidths that are suitable for real-time television.

The fourth wavelength, in the selected set for comparison, is 0.85 μm. This is the near-visible wavelength generated by the gallium arsenide (GaAs) laser. At this short wavelength, a system is considered that employs incoherent (power) detection; i.e., photon counting. Therefore, the phase distortions caused by seeing conditions are immaterial. Although photon counting is unfamiliar in microwave systems, it is normal in many astronomical experiments and in various systems that detect low levels of incoherent light. Such a system is attractive from several standpoints:

(1) Astronomical technology is more directly utilized.

(2) Site-selection and seeing problems are alleviated.

(3) Surface accuracy requirements of the ground telescope are alleviated.

(4) Pointing requirements of the ground telescope are relaxed to some extent.

However, the advantages are offset to a large degree by the loss of discrimination against background radiation and the lack of a high-efficiency laser in this band.

The numerical estimates for this band will represent the best case—communication at night from a dark planet. The methods of discriminating against the background of a sunlit target planet and the daytime sky involve a very complex set of trade-offs that will be indicated only briefly. The reasons for selecting the GaAs laser from the many types that emit in the visible or near infrared are as follows: small rugged construction, fair efficiency (2% is about the best without cryogenics), and ease of modulation at high rates. The last feature allows transmission in brief, intense pulses so that the peak power will exceed the background radiation without requiring excessive average power. The recently developed frequency doubled neodymium-doped yttrium aluminum garnet (YAG) laser (Ref. 5) at a wavelength of 0.53 μm, is also a possible choice. The estimated performance characteristics are very close to the GaAs laser, so the assumption is made that the two systems are essentially equal, and only the GaAs system is considered.

The fifth and final wavelength considered is 3.8 μm, intermediate between the 10-μm and 0.85-μm bands. This band appears to have most of the advantages of both the 10-μm and 0.85-μm bands, and few of the disadvantages. Photon counter detection is feasible, background noise is low, and an excellent atmospheric window exists. Unfortunately, at the present time this band has neither an efficient laser, nor an efficient detector. However, it appears that an efficient gas laser could be built using schemes similar to those in the N_2–CO_2 laser. The discussion presented in this report on the 3.8-μm system is brief and tentative because of the missing components.

Combined problems of clouds, turbulence (astronomical seeing), economics,[1] and geopolitics dictate that any ground weather-dependent system will have incomplete coverage of the celestial sphere and will be subject to random interruptions. Before such links become practical, this problem must be solved. The solution could be through use of an orbiting or mobile relay station, or a system for spacecraft data storage combined with rapid bulk data dumping during good weather, or a hybrid of these approaches with one system serving as a backup for the other. Realistically, the use of weather-dependent frequencies will in turn demand the use of spacecraft bulk data storage. This report is based on the assumption that photographic or other storage techniques can and will be space qualified for interplanetary missions.

B. Range Equation and Communications Capability

The communications range equation is one very important basis of comparison for the five frequencies selected. This equation provides the means of determining how much transmitted power is picked up by the receiving antenna. Among other things, this equation depends upon the product of the diameters of the transmitting and receiving antennas, $D_R D_T$, and this product result indicates antenna sizes that will satisfy mission communication requirements.[2] If these sizes should be impractical, allowances are made for a number of ground antennas, N_R, operating as an array. In this case, $N_R^{1/2} D_R D_T$ is the appropriate quantity. The range equation in this convenient form is

$$N_R^{1/2} D_R D_T = \frac{4R\lambda}{\pi}\left(\frac{P_R}{\eta P}\right)^{1/2} \qquad (1)$$

[1]Redundant ground stations are not economically practical (Ref. 1).

[2]This size product constitutes an important system parameter, not a figure of merit. For example, the Hale telescope at Palomar constituted an extremely challenging and costly project, even though its diameter is only 17 ft. However, such considerations inevitably become highly speculative and subjective; they are intentionally omitted from this report.

where

R = range to the spacecraft

λ = wavelength of the data carrier

P = (raw) electric power to the transmitter

P_R = received power

η = product of all pertinent efficiencies, viz., transmitter power conversion efficiency, antenna efficiencies, atmospheric transmission (when applicable), and others discussed in subsequent sections

To use Eq. (1), the amount of power P_R that is needed to receive the data must be known. The amount of power needed depends upon the amount of noise in the receiver as specified by its spectral density Φ, which has units of power (W) per unit frequency interval (Hz); or, since Hz = s^{-1}, a W/Hz is a W-s, or J, an energy unit. The portion of the noise power that cannot be distinguished from signal occupies the same frequency band as the information, so that the appropriate noise power level is the product $B\Phi$, where B is the information bandwidth. It is normally required that the received signal power be at least ρ times the noise power, where ρ is the minimum signal-to-noise ratio (SNR) necessary to hold the probability of error in data interpretation below an acceptable maximum. So finally we have

$$P_R = \rho B \Phi$$

to substitute for P_R in Eq. (1). The result is

$$N_R^{1/2} D_R D_T = \frac{4\lambda}{\pi} \left(\frac{M\Phi}{\eta} \right)^{1/2} \tag{2}$$

where several factors are combined into the quantity M, defined by

$$M = \frac{(\rho B) R^2}{P} \tag{3}$$

The significance of M is that it specifies the difficulty of the communications job in a particular mission. The product ρB is closely related to the rate at which the communication link can transfer information (bits/s). It should be noted that an increase in one of the quantities in the numerator of M corresponds to a more difficult communications task; namely, greater information rate or longer range. An increase in the (raw) power available, which makes the task easier, enters the denominator to decrease M.

For the sake of brevity and clarity, a single value of M is selected for use throughout this report. This approach allows emphasis on comparisons of communication links without excessive digression on mission requirements. The single value does not imply significant loss of generality because the results can be changed for some other value of M by applying the appropriate scale factor. However, a suitable mission must first be well enough defined to estimate a more appropriate value for M. Meanwhile the selection is

$$M = 5.3 \times 10^5 \text{ AU}^2/\text{J} = 1.274 \times 10^{29} \text{ ft}^2/\text{J}$$

This value applied, represents a formidable task, for example in acquiring slow-scan, real-time TV from Mars with only 1 kW of raw power.

As an example of how this M value may be selected, the following are substituted in Eq. (3):

$$P = 1 \text{ kW}, \qquad \rho B = 10^8 \text{ Hz}, \qquad R = 2.3 \text{ AU}$$

This value of range will be used as standard for an extended exploration of Mars (consistent with the idea of using a weather-dependent link for the data that are routine but voluminous). This range is barely less than the maximum range of 2.52 AU, and 4.4 times the minimum of 0.52 AU. The choice of $\rho B = 10^8$ could result from transmitting 10^6 bits/s at a reasonably high SNR. The bit rate in turn could result as $316 \times 316 = 10^5$ TV picture elements per frame, times 10 bits of information per element (color), times one frame per second = 10^6 bits/s.

This method of choosing M should not be construed as emphasizing Mars missions for the weather-dependent frequencies. Rather, the major planets are of somewhat greater interest in this study.[3] The preceding discussion of Mars TV serves merely as a form of normalization to compare the selected capability to the more familiar Mars missions. Table 1 and Fig. 1 show the meaning of

[3]A new problem comes into play here, as shown in Table 1. The two-way propagation time may exceed the time for which existing weather conditions may be extrapolated; for Pluto, the commanding station is not the receiving station. However, these problems do not appear to impose a fundamental difficulty. Since the spacecraft is assumed to have an invariant power input (e.g., solar power), it would be reasonable for the spacecraft to repetitively transmit a given block of data until word is received from earth that the block has been received with an acceptable error rate. This technique implies a spacecraft memory that is addressable in blocks of perhaps 10^7 to 10^9 bits. This is a requirement that has been solved with high reliability in computer installations by use of various mechanically controlled devices. The entire two-way system could be machine-controlled, and should not require human intervention.

Table 1. Combinations of SNR, bandwidth, raw spacecraft power, and range that yield selected value of $M = 5.3 \times 10^5$ AU²/J

Planet	Range, AU	$\rho B/P$, Hz/W	Two-way time delay, h
Mars	2.3	1.0×10^5	0.6
Jupiter	5.3	1.9×10^4	1.5
Saturn	9.6	5.7×10^3	2.7
Uranus[a]	19.2	1435	5.3
Neptune[a]	30.1	581	8.4
Pluto[a]	39.5	340	11.0

[a]Possible major weather changes during two-way propagation time.

the chosen value of M for missions to the outer planets. The selected ranges occur when earth and planet form a right angle at the sun. The graph (Fig. 1) gives bandwidth times SNR vs raw power for these ranges.

Equation (2) may now be used to find the antenna aperture products. Subsequent sections depict these products. To do this, each frequency band is treated separately, deriving a conceptual system model for each band. Each model is developed in such a way as to maximize the attractiveness of the equipment within the framework of realistic engineering design. Interpretation of the results is reserved for the conclusions presented in Section VIII.

III. Description of an X-Band System

The 3–4 cm band is of particular interest for at least three reasons: (1) It is near the lower bound of weather-dependent frequencies. (2) It has an old and well-established technology that allows accurate predictions of hypothetical future system performance. (3) It is at present the approximate upper frequency bound for the efficient operational use of large ground antennas (see Ref. 1) whose size is limited mainly by economical factors. The largest antenna structure that is currently considered economically sound (roughly 200-ft diam) works with reasonable X-band performance in all but the most severe weather conditions.

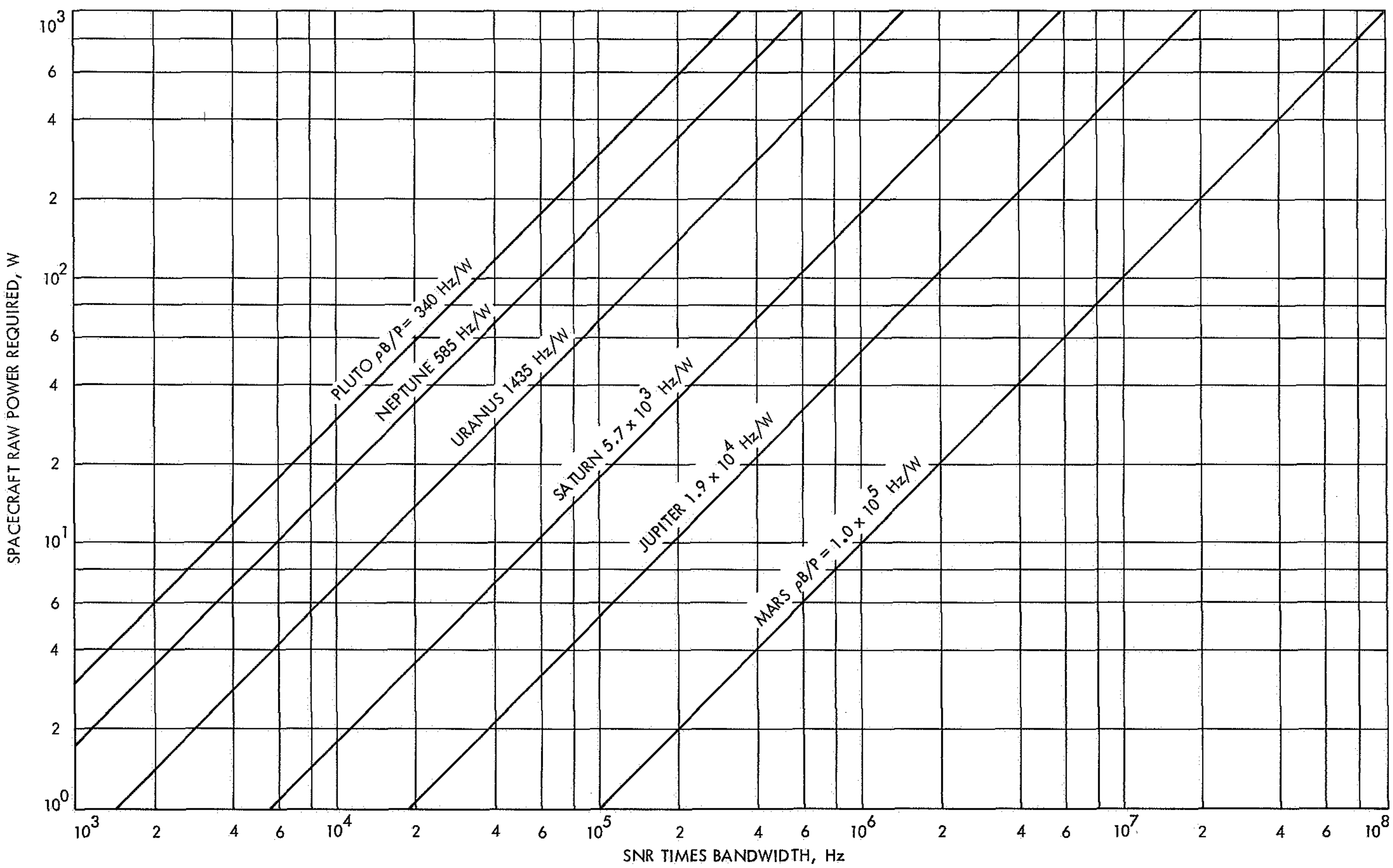

Fig. 1. Significance of choosing $M = 5.3 \times 10^5$ AU²/J

A. Effect of the Weather

For an X-band system, performance may be degraded in either (or both) of two ways. The first is by atmospheric water content (humidity, clouds, and rain), and is independent of engineering. The second is by wind distortion of the antenna structure, and is related to the cleverness of the design engineers. Because the link is to be used only under good conditions, a study of the effects of weather is presented to determine link outage times.

The effects of rain, clouds, and water vapor upon X-band propagation have been studied by many authors. Two recent survey papers constitute excellent sources (Refs. 6 and 7). These studies provide a cross reference to most of the prior studies. The effect of water is serious to the extent that only rather dry climates (5–20 in. of rain per year) could be justified for the location of high-performance, deep space data-reception installations. This being the case, high humidity or heavy cloud formations will be statistically related to rain. Ordinary dry-climate humidity (roughly 5–10 g/m^3) and ordinary cloud formations do not grossly affect X-band performance.

The effect of rain is a serious matter, as shown in Fig. 2. This is based on a slab model for the rain (fairly good above 30 deg elevation), limited experimental data presented in Ref. 8, and an analytical model given in Ref. 9. In this figure, low (near-freezing) temperature is selected to eliminate humidity considerations. Although more experimental data might refine these computed results, they are certainly good to within a factor of 2 in dB. The losses are computed relative to a system having a noise temperature of 20°K in clear weather (10°K for the total of receiver and transmission line contributions). The choice implies equipment that is advanced, but not beyond laboratory state of the art. To eliminate the elevation-angle dependence shown in Fig. 2, the performance may be averaged from the selected minimum of 30 deg to zenith, properly weighted by solid angle, as shown in Fig. 3. Also included in this figure is the water-vapor effect, where 100% humidity is assumed during rain. Roughly speaking, a drizzle has only a moderate effect (1–3 dB), a light rain is serious, and medium to heavy rain effectively blacks out the system.

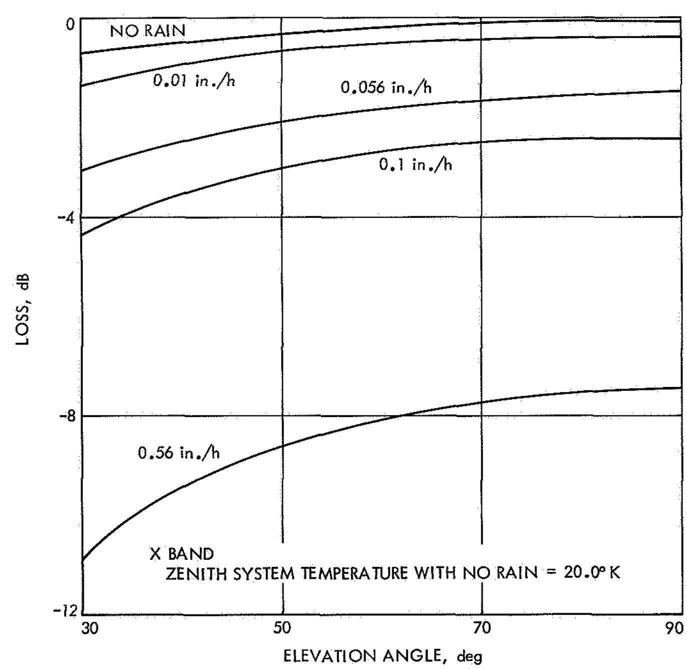

Fig. 2. System degradation vs elevation angle and rain rate, low temperature (32°F)

Figure 4 shows the calculated surface tolerance loss, as a function of wind (Ref. 10), of the NASA/JPL 210-ft advanced antenna system if it were used at X-band.

The breakpoint at 45-deg el is caused by the fact that the surface is set at this angle to minimize gravity effects. As with rain, elevation dependence may be averaged out, yielding the result shown in Fig. 5. Possibilities for grossly reducing wind degradation do not appear encouraging. This antenna was carefully designed for high wind resistance, and is considered a near-optimum state of the art design.

B. Rain Statistics

Although little can be said about wind statistics without detailed knowledge of the site, the same is not true of rain statistics.[4] Statistically good predictions may be made based upon only readily available information, such as the annual rain rate.

Any site may be described in terms of a few simple rain parameters: (1) total annual rate, (2) hours of rain per year, and (3) rain rate probability distribution. It should be noted that these factors are not independent, since summation over a year's time of rain rate times time at that rate must equal the annual rainfall. Figure 6 shows typical rain-rate statistics (see Ref. 6) for three temperate sites, together with simple predictions from annual rainfall data. Figure 7 shows a more detailed

[4]Long-term wind data are presently being taken at the Goldstone Calif. Deep Space Instrumentation Facility. Pending completion of this program, subjective considerations that indicate wind outage times comparable to rain outage times are used.

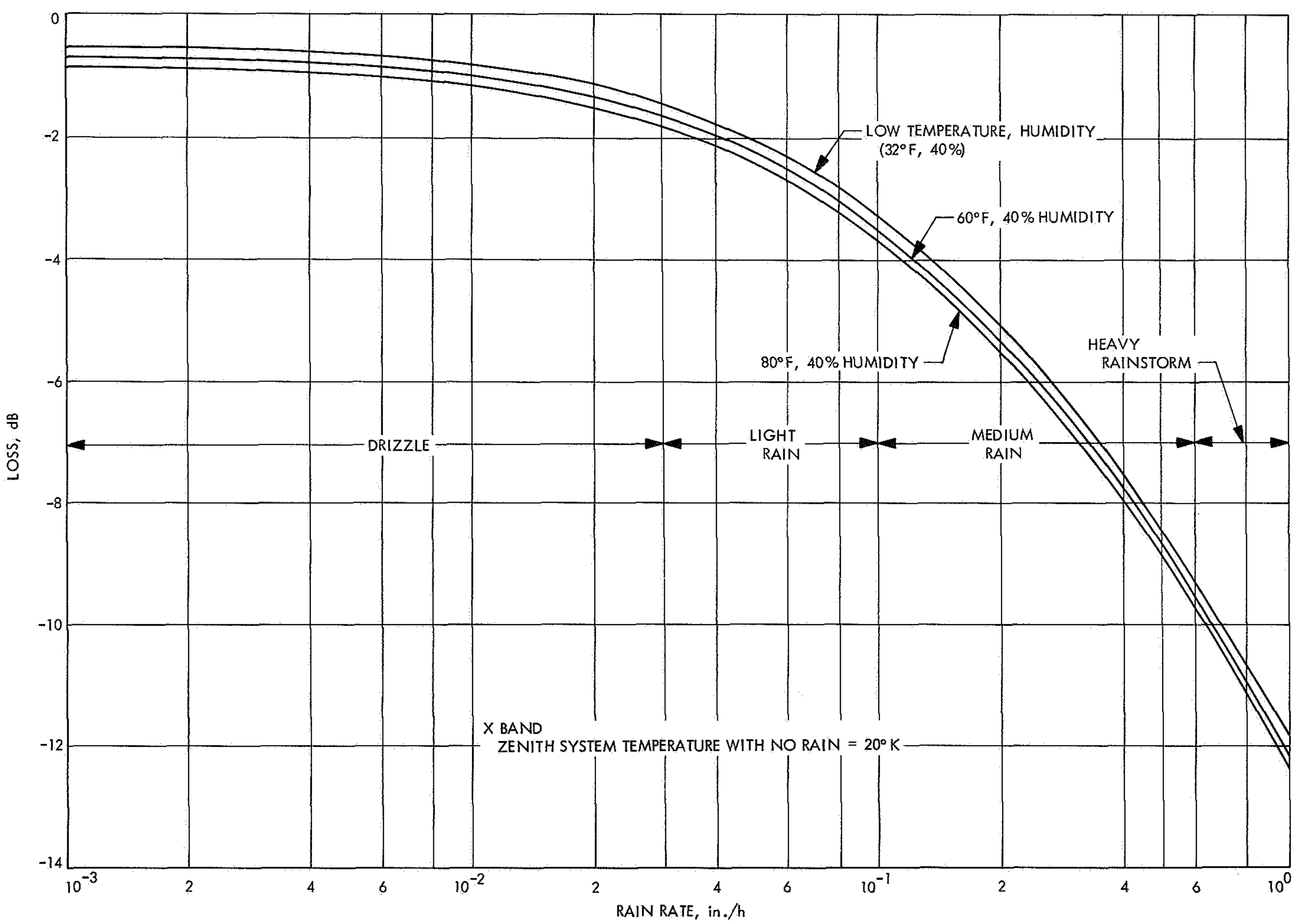

Fig. 3. System degradation vs rain rate, elevation averaged

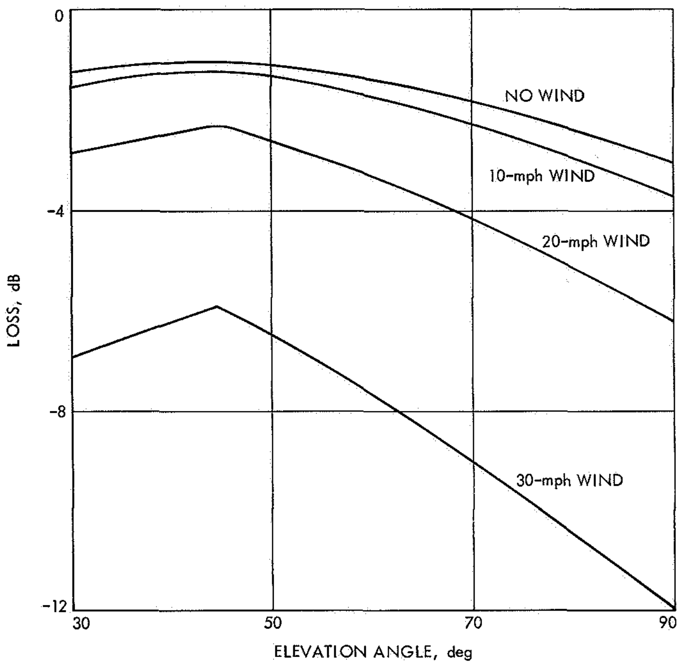

Fig. 4. Surface tolerance loss of 210-ft antenna vs elevation angle and wind—X-band

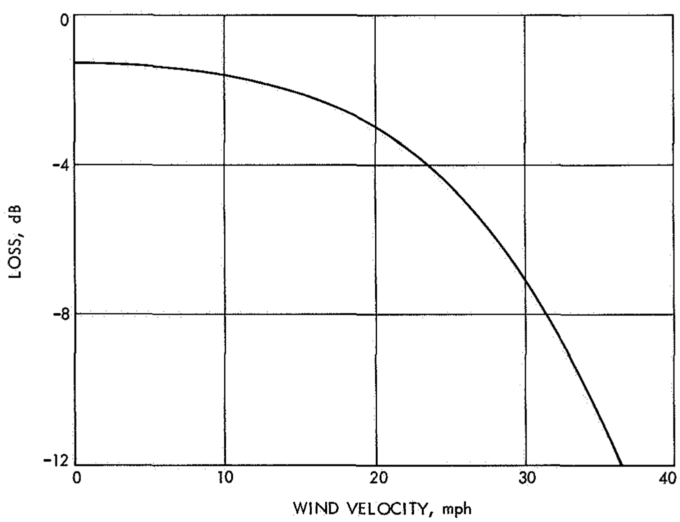

Fig. 5. Surface tolerance loss of 210-ft antenna vs wind, elevation averaged—X-band

comparison of measured and predicted rain statistics for Washington, D.C. Figure 8 uses combined data from previous figures to show the approximate percentage of time for which a specified system loss is exceeded for the annual rainfall at typical sites.

Curiously, the total hours of rain per year is roughly constant (400–600 h/yr, or about 5% of the time) for temperate sites (see Ref. 6). The factors that appear to vary the most with site location (e.g., New England vs Southern California) are the mean rain rate during rain and the probability of rain vs time of year. The major advantage of a dry climate, therefore, is not less likelihood of rain, but rather a smaller effect during the rain.

C. System Performance

Based on Figs. 5 and 8, choices of ground-antenna aperture efficiency and system noise spectral density may be made. For the range equation estimates of Section II, a loss of 2 dB is selected owing to a loss of surface tolerance corresponding to a 15-mph wind. It is further assumed that the small percentage of time (presently undefined, but probably less than 5%) for which this loss is grossly exceeded may be spent profitably for equipment maintenance and need not be included as a degradation factor. Similarly, it is assumed that the small percentage of time for which significant rain degradation occurs can profitably be used for station functions other than data acquisition.[5] Thus, the effect of rain is ignored completely, and system spectral noise density will be based on clear weather conditions of 80°F and 40% humidity.

One of the key spacecraft performance parameters is the efficiency of the transmitter. A detailed survey of spacecraft transmitters referencing 88 other papers, has been published recently (Ref. 11). Also of interest is a survey of general microwave-tube characteristics presented in Ref. 12. Unfortunately, the choice of transmitter type, and the resulting performance, is a function of many mission- and time-dependent features, such as lifetime, reliability, magnetic field, weight, and size. Furthermore, these characteristics are not constrained by fundamental limitations, but rather are controlled by the product of engineering effort and time.

Therefore, it is assumed that any existing laboratory device could be given the attributes of high reliability, long life, reasonable weight/size, and possibly electrostatic focusing (freedom from magnetic field) with adequate research support. With this assumption (consistent assumptions have to be made with lasers and millimeter-band devices), a rough prediction of future capabilities can be made. As an example of present technology, an

[5]Virtually all large installations (e.g., tracking stations and computer facilities) must schedule at least a percent of their time for preventive maintenance. There is no obvious reason why this work has to be scheduled on a weather-independent basis (with obvious atypical exceptions).

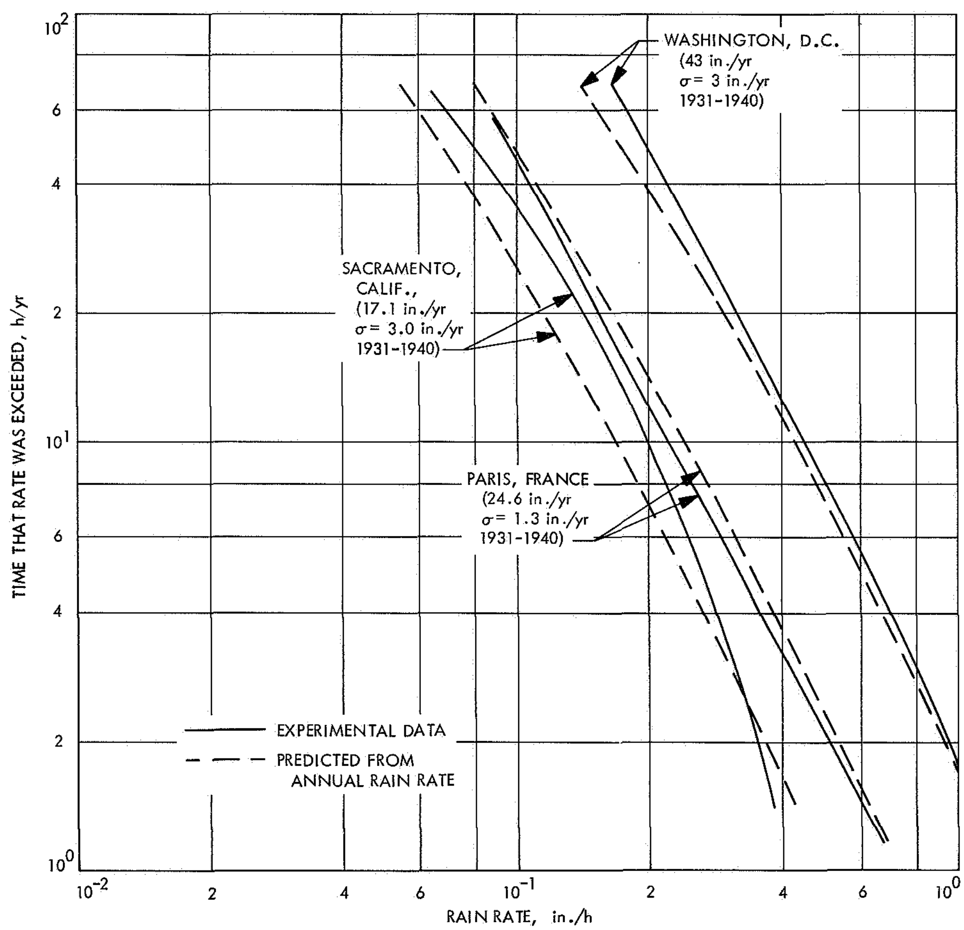

Fig. 6. Rain rate statistics

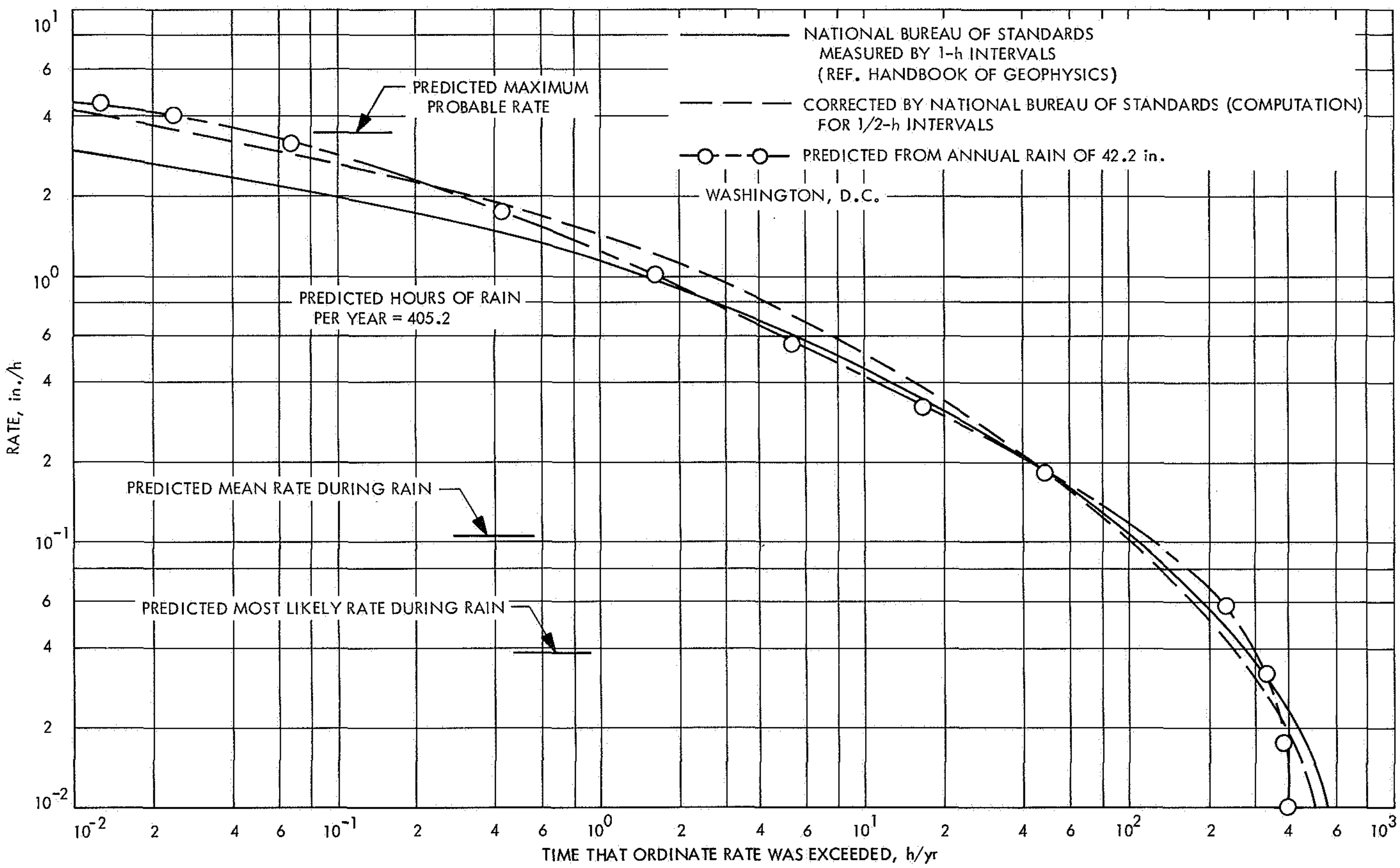

Fig. 7. Comparison of measured rain data with simple prediction from annual rate

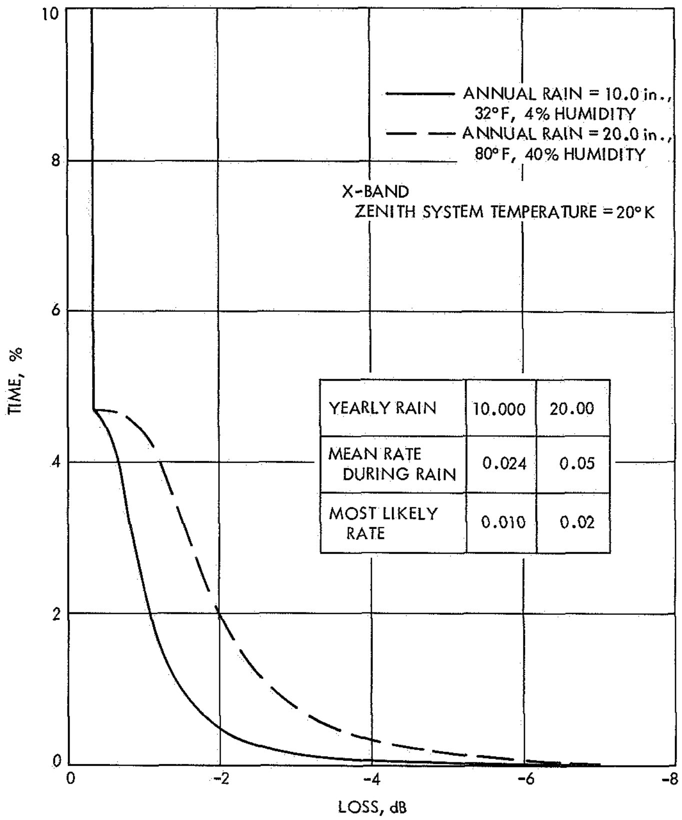

Fig. 8. Maximum percentage of time for which a given rain loss may occur

interesting laboratory device has been reported (Ref. 13) that operates at 2800 MHz, with power output of 1 kW continuous wave (CW), efficiency of 65%, and bandwidth of about 25 MHz. This design can be scaled to higher frequencies, such as X-band.

Total tube power output does not appear to be a basic problem; X-band tubes are already available for ground use in the 10–100 kW CW region. The problem of large heat dissipation in space, although not completely straightforward, is not unduly difficult, and it is receiving extensive engineering attention by several organizations.

In choosing spacecraft transmitter parameters, it is assumed that, for the period 10–20 yr in the future, suitable spacecraft X-band amplifiers could be made available in the range of 10–10,000 W, all qualified for long-life, high-reliability applications. Based on data in Ref. 13 and assumed minor compromises for spacecraft application, a beam efficiency of 50% is selected. An additional multiplicative efficiency factor of 90% is selected to include such considerations as conversion from raw spacecraft power to tube power and power for the driver amplifier. An overall efficiency of about 45% is chosen for conversion of raw spacecraft power to X-band microwave power.

The remaining key X-band system performance factors relate to the spacecraft antenna. Two classes of antennas are typical candidates—parabolic reflectors (paraboloids) and array devices. Parabolic reflectors are characterized by high reliability, moderate aperture efficiency (60–70%), and simplicity of design. Array devices are characterized by a difficult reliability problem (generally solvable), a complex design problem, and high aperture efficiency (80–90%). Each of these classes may be further subdivided into pre-erected (on earth or in orbit) and unfurlable types. The array antenna does not at present appear attractive for the high-gain application considered here. The typical disadvantages include the great complexity, difficulty of design variation (as for different gain), and lack of compatibility with reliable unfurling techniques.

Having selected the paraboloid, the choice of unfurled or pre-erected type is left open, since it does not appear pertinent to this report. Either approach is a straightforward mechanical/structural design problem, and microwave performance will be virtually unaffected by this decision. Based on existing paraboloid technology (Ref. 14), an aperture efficiency of 65% is selected. With this efficiency, a multiplicative factor of 90% is used to account for such factors as polarization loss to the ground antenna and transmission-line loss in the spacecraft.

Finally, the pertinent X-band system performance factors are summarized in Table 2.

Table 2. The X-band system performance parameters

Parameter	Value
Frequency	8.450 GHz
Wavelength	3.55 cm
Receiving system noise temperature, 30 deg el to zenith	22.41°K
Receiving system noise spectral density, $\Phi = kT$	3.095×10^{-22} W/Hz
Spacecraft dc power-conversion efficiency	90%
Transmitter beam efficiency	50%
Spacecraft antenna aperture efficiency	65%
Transmission line and polarization loss	90%
Ground antenna aperture efficiency (includes 15-mph av wind)	41%
Product of all efficiencies, η	11%
$N_R^{1/2} D_R D_T$ (for $M = 1.274 \times 10^{29}$ ft²/J)	2.78×10^{3} ft²

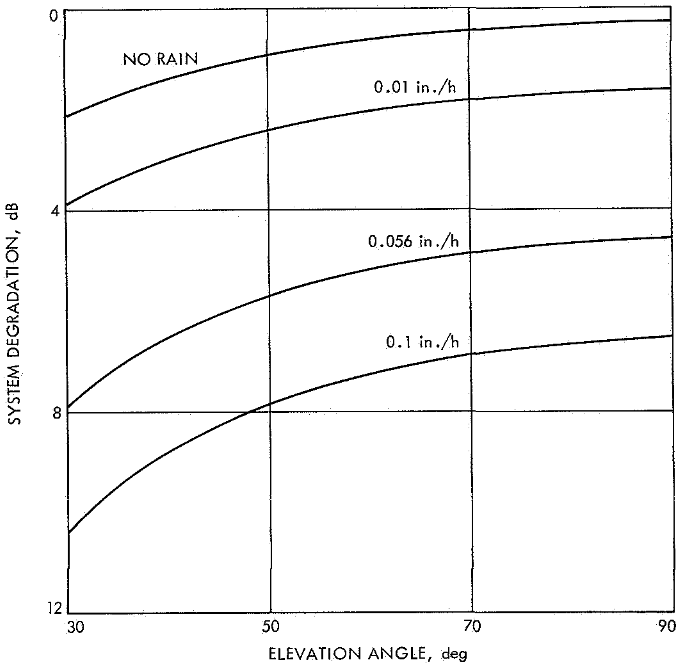

Fig. 9. Degradation vs elevation angle as a function of rain rate—millimeter system

IV. Description of a 3.3-mm Wavelength System

The distinctive characteristics of a millimeter wavelength system are: (1) potentiality for a wider bandwidth than that available at the lower conventional microwave frequencies, (2) proximity to the upper frequency limit for RF device technology and low-noise amplifiers, and (3) moderate degradation of sensitivity during periods of high humidity and light rain conditions.

As an additional characteristic of considerable interest, interference problems are very minimal at millimeter wavelengths compared to the lower microwave frequencies. This is primarily because of lower user activity and the higher directivity of the propagating wave. Reference 15 describes the use of this feature to advantage with a site location adjacent to a populated area.

A. Weather and Ground Antenna

Much of the previous material, and especially the rain statistics developed for the X-band system (Section III), is applicable to this system. The millimeter wavelength system is more sensitive to both atmospheric water content and antenna wind distortion. Therefore, only dry climates can be considered for tracking station installations. The effect of atmospheric loss as a function of elevation angle and humidity has been investigated theoretically and experimentally (Ref. 16). Although good experimental data are not presently available, the attenuation of rain at millimeter wavelengths has been extensively studied theoretically (Refs. 17–20).

High rain rates produce serious system performance degradation, as shown in Fig. 9, where the effect of humidity has been minimized. Figure 10 shows the system performance degradation averaged in elevation angle from 30-deg zenith caused by water vapor and rain rate. These calculations are made using the atmospheric attenuation appropriate for the JPL Goldstone Tracking Station at an elevation of about 3500 ft. As in the X-band system, a drizzle has a moderate effect, a light rain is serious, and heavy rains cause an effective blackout. The accuracy of these data is probably within a factor of 2 in dB. Figures 11 and 12 show the predicted effect of wind on operative efficiency for a 30-ft antenna. This antenna is basically a structural scale of the S-band NASA–JPL 210-ft advanced antenna system except for the following parameters:

(1) Panel manufacturing accuracy = 0.003 in. rms.

(2) Panel setting accuracy = 0.003 in. rms.

The panel manufacturing error for the present JPL 30-ft antenna is 0.015 in. rms, so that new techniques will be required. Machined panels or special honeycomb structures have been suggested. The required panel-setting accuracy appears to be feasible for a 30-ft antenna. Plans are presently underway to investigate the possibility of using servomechanisms to individually position the panels of the JPL 30-ft antenna (Fig. 13) at the Goldstone Venus Station to reduce the effect of gravity. Extension to a closed-loop, optical-sensor system (Ref. 21) could greatly reduce thermal, gravity, and wind effects. An alternative to the individually controlled panels is a permanent wind shield, which is more feasible with a 30-ft antenna than with a 210-ft X-band antenna.

Possibilities include an astrodome (Ref. 22) or an inflatable radome that can also reduce thermal effects, and provide additional weather protection. An alternative to the panel-construction techniques is illustrated by the 33-ft solid paraboloid recently completed for the National Radio Astronomy Observatory by Rohr Corporation to be installed on Kitt Peak, Ariz. This surface has an overall surface tolerance of 0.0042 in. rms at zenith.[6]

The assumed 30-ft antenna can be improved approximately 1 dB with an advanced design (Fig. 12) if the

[6]Gilligan, R., private communication. Rohr Corp., San Diego, Calif.

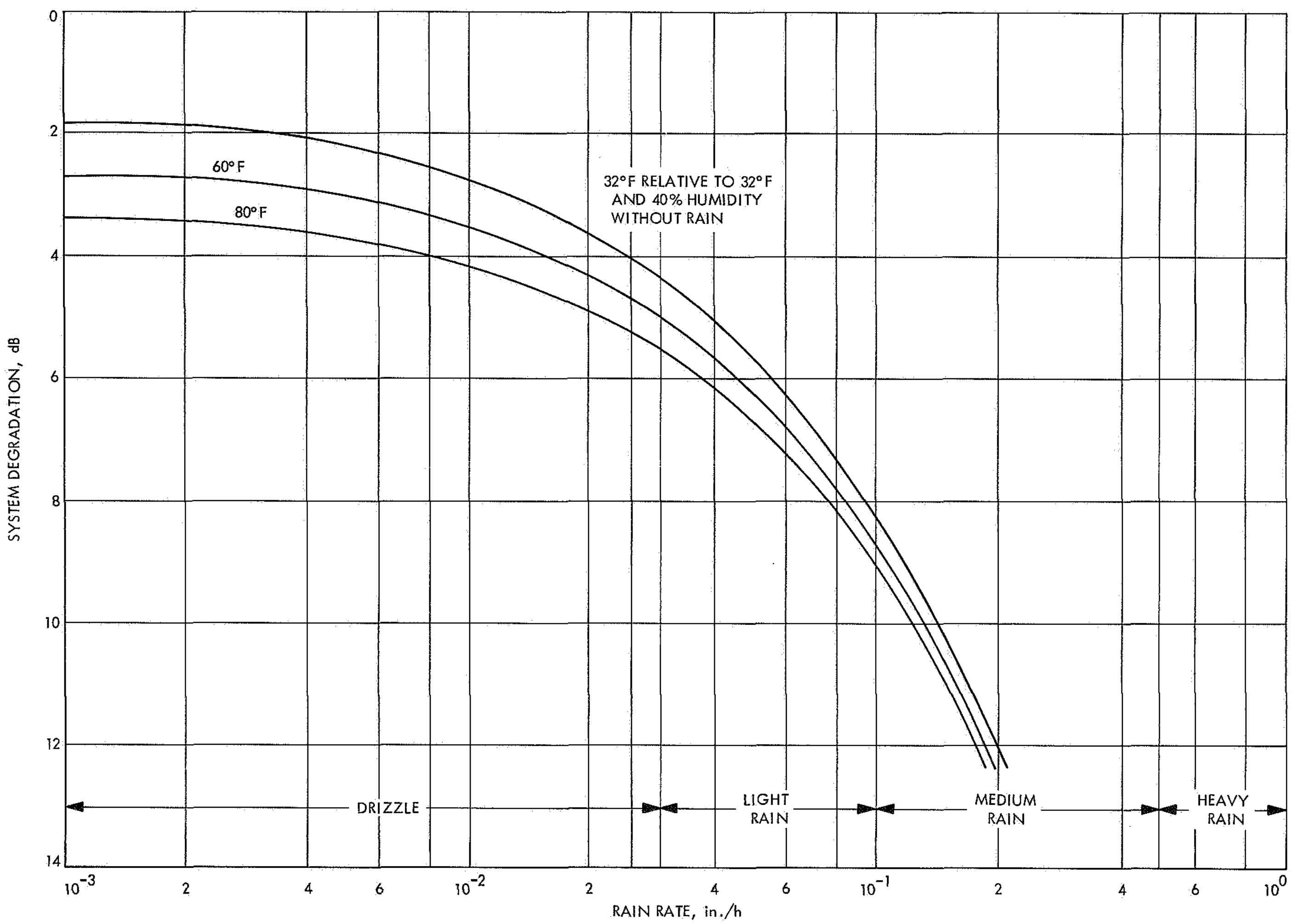

Fig. 10. Degradation vs rain rate with averaged elevation angle as a function of temperature—millimeter system

panel manufacture and setting accuracies are reduced to 0.002 in. and the gravity, wind, and thermal design is improved by a factor of 10. These requirements may not be considered economically excessive when compared with the cost of a 210-ft antenna. The pointing problem of a 30-ft antenna is comparable to that of the 210-ft antenna at X-band, and does not appear to be a major consideration.

B. Ground Receiver

The ground receiver for the 90-GHz system requires special attention, as it is the weak link in existing technology. In this section, basic principles and the present state of the art are reviewed briefly.

A fundamental limit for amplifier noise is given by quantum noise (Ref. 23).

$$T_a = \frac{hf}{k}$$

where

h = Planck constant = 6.6256×10^{-34} J

k = Boltzmann constant = 1.38054×10^{-23} J/°K

f = frequency, Hz

This quantum noise, which is dominant for very short wavelengths, is significant at 90 GHz with a value of 5°K, and must be considered for any low-noise millimeter amplifier. Traveling-wave masers have been fabricated that are operational at 8 mm (Refs. 24 and 25). Maser and parametric amplifier techniques are being investigated for the shorter 3-mm wavelength applications.

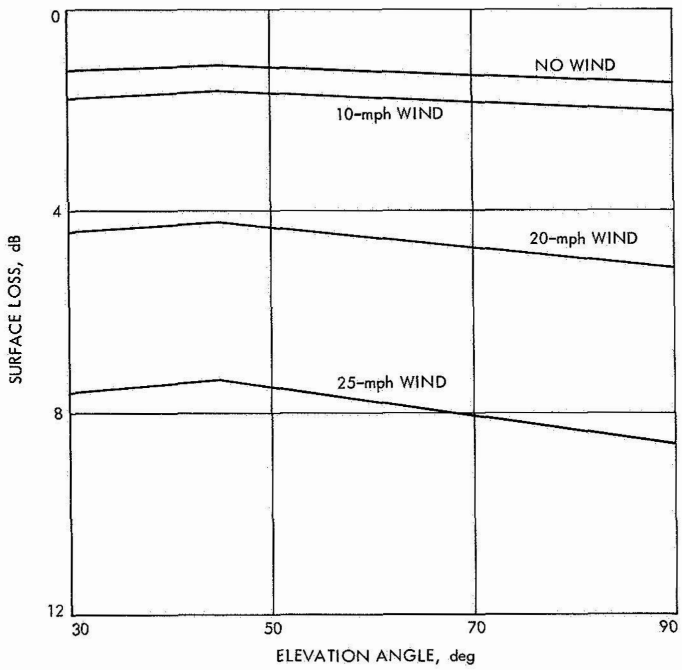

Fig. 11. Assumed 30-ft antenna surface tolerance loss vs elevation angle as a function of wind velocity—millimeter system

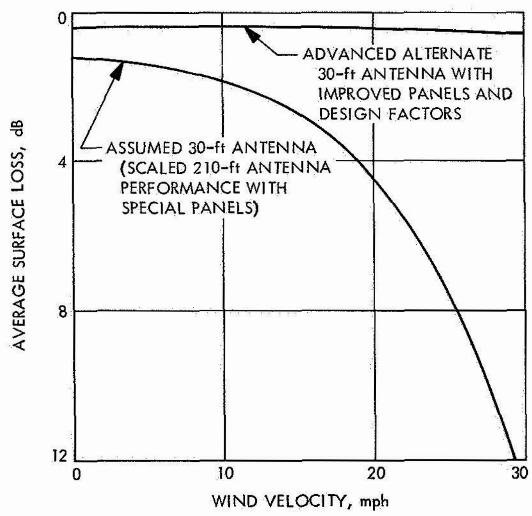

Fig. 12. Surface tolerance loss vs wind velocity, averaged elevation angle—millimeter system, 30-ft antenna

The planar annular varactor (Ref. 26), with a predicted cutoff frequency of about 1500 GHz, is being considered for use in a millimeter wave parametric amplifier. A major difficulty is the extremely high pump frequency required for very low noise operation. It is generally conceded that the maser amplifier provides the ultimate

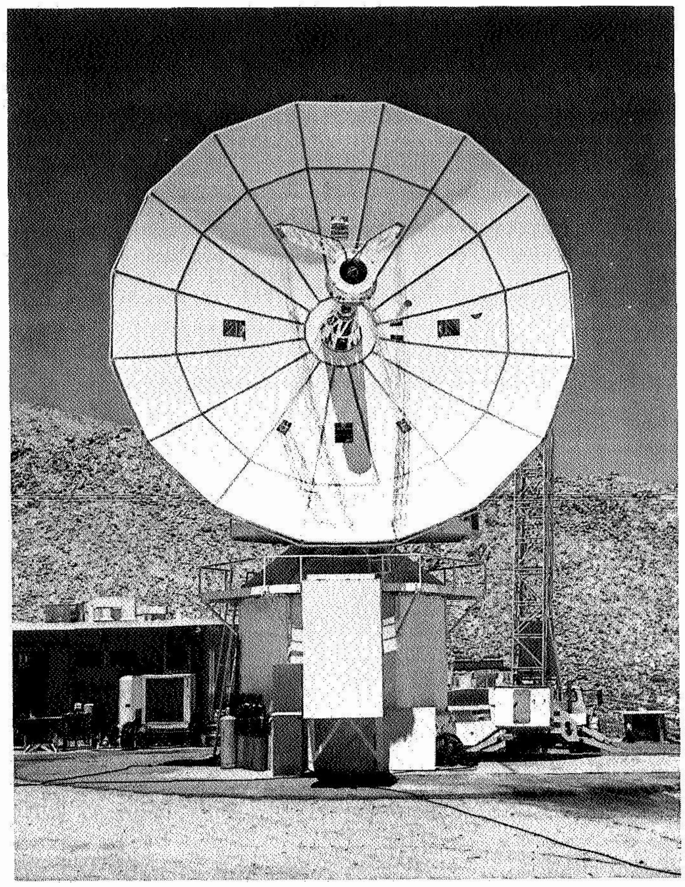

Fig. 13. The JPL 30-ft antenna—Goldstone Venus Station

in low-noise-temperature performance. A major operational advantage of the saturated maser that is ordinarily unavailable with the parametric amplifier has proven to be the relative gain stability despite pump-power variations. The thermal noise contribution T_M for a traveling-wave maser is given by (Ref. 27):

$$\frac{T_M}{T_B} = \frac{\frac{1}{I} + \frac{\ell}{g}}{1 - \frac{\ell}{g}}$$

where

T_B = bath temperature, °K

I = inversion ratio

ℓ = overall amplifier structure loss, dB

g = overall amplifier electronic gain, dB

It is possible to build masers in which this ratio is less than 1 in the microwave regions. With proper materials and slow wave structures, this should also be feasible at millimeter wavelengths. Feasibility tests have been performed (Ref. 28) on a 94-GHz cavity maser, using iron-doped rutile as the active material, with a pump frequency of 218 GHz. No maser gain was obtained, although interactions between the pump energy and spin system were observed.

Nonconventional maser amplifiers involving mixing action have also been proposed for millimeter operation (Ref. 29). The capability for the tremendous advances in (maser) amplifier operating noise performance, achieved at the lower frequencies, should extend to the millimeter wavelengths. Consequently, the assumption is made that the millimeter system has a receiver temperature of 10°K at the input to the liquid-helium-cooled structure.

Operational low-noise receiving systems are plagued by relatively high transmission-line noise contributions caused by input calibration components; e.g., the waveguide switches required for system performance. Cooled transmission line techniques, presently under consideration for lower frequency microwave systems, are applicable. Although waveguide losses are considerably higher at millimeter frequencies, the effect is somewhat offset by shorter component and waveguide lengths. It is expected that the total input line loss can be held below 0.60 dB, which corresponds to a 10°K noise contribution with liquid nitrogen transmission line cooling.

C. System Performance

The receiving system losses for the millimeter system study using the proposed 30-ft antenna system are:

(1) Atmosphere (av 0.30-deg el to zenith) = 0.69 dB.

(2) Antenna surface = 1.21 dB.

(3) Input transmission line = 0.60 dB.

Atmospheric loss and system spectral noise density are based on clear weather conditions at 80°F and 40% humidity. It is assumed that the times of antenna degradation or atmosphere loss, due to high wind or rain rates, can be profitably used for equipment maintenance (Fig. 14).

The present state of the art with high-power transmitters is adequately described elsewhere (Ref. 30). Hughes Research Laboratories, Malibu, Calif., have developed a high-power traveling-wave tube amplifier (Model 819H) that produces 6 kW of CW power at 5.5 mm, with 30% efficiency, using a depressed collector. They also have a 94-GHz unit (Model 814H) having an

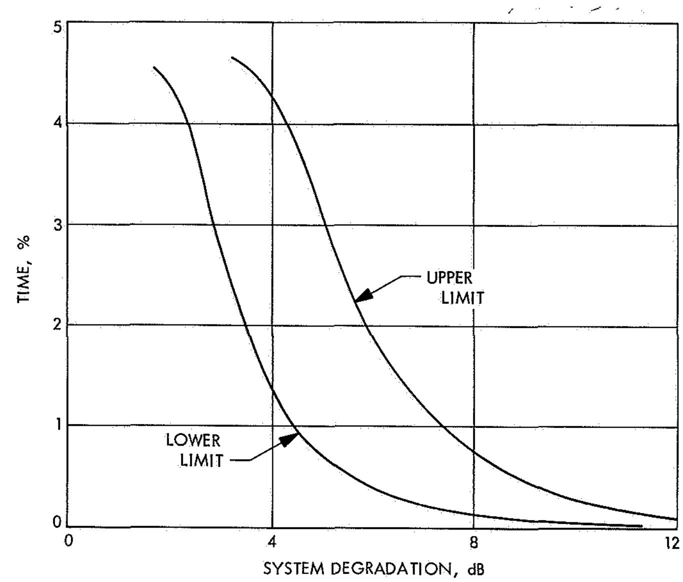

Fig. 14. Maximum percentage of time for which a given system degradation may occur for the millimeter system

output power of 150 W, 20-dB gain, and 20% efficiency with air cooling. It is assumed that, as in the X-band study, a millimeter transmitter could be made available, with the necessary operating parameters for spacecraft usage, in the next decade. With the realization that a small hardware penalty is required for the shorter wavelengths, the efficiency of 0.45 for the X-band spacecraft dc-to-transmitter RF power efficiency is reduced by 10 to 41%.

The overall system performance data are summarized in Table 3. A spacecraft antenna of 17.3-ft diam is required with the single proposed 30-ft ground antenna.[7] Difficulty with the spacecraft dc-to-RF conversion or the receiving amplifier noise temperature performance could be made up with larger antennas or antenna arrays. It has been pointed out (see Ref. 8) that rainfall rate is poorly correlated between stations even when they are spaced relatively close. In a small receiving array, this advantage could be used to reduce weather dependence if an array is required. If the given parameters are satisfied, a larger antenna or an array can be used on the ground to reduce the spacecraft antenna dimensions. For example, a 60-ft antenna, or an array of four 30-ft antennas similar to the Ohio State adaptively phased configuration (Ref. 31), would require an 8.6-ft diam spacecraft antenna.

[7]It is worth noting that an associated half-power beamwidth of about 0.04 deg and an implied pointing-accuracy requirement of better than 1 min of arc, together with the large physical size, suggests a difficult pointing-system design problem.

Table 3. The millimeter band system performance parameters

Parameter	Value
Frequency	90.0 GHz
Wavelength	0.333 cm
Receiving system noise temperature, av 30 deg el to zenith	71°K
Receiving system noise spectral density	9.80×10^{-22}
Spacecraft dc to transmitted RF efficiency	41%
Spacecraft antenna aperture efficiency	65%
Atmospheric, transmission line, and polarization loss	70%
Ground antenna aperture efficiency (assuming a feed efficiency of 0.65)	49%
Product of all η	9%
$N_R^{1/2} D_R D_T$ ($M = 1.274 \times 10^{20}$ ft²/J)	518 ft²

Some of the problems pertaining to adaptive antenna techniques for millimeter-wave applications have been studied (Ref. 32). A 60-ft ground antenna with the same performance as the assumed 30-ft antenna could be achieved with panel manufacturing and setting accuracies of 0.002 in. rms. Gravity, wind, and thermal designs could be improved by a factor of 10 (possibly with the panel servo system technique) over the 210-ft antenna scaled design.

D. Alternate Schemes

A site at a higher elevation, with an attendant reduction in atmospheric loss and system temperature, is considered to compare the trade-offs. An elevation of 7500 ft, appropriate to the southwestern part of the United States, reduces the averaged (30 deg el to zenith) atmospheric loss and system temperature to 0.38 dB and 52°K, respectively. A list of ground receiving system possibilities is given in Table 4. It is noted that neither increased elevation nor advanced antenna design produces a drastic improvement. In practice, it would probably be more reasonable to adjust the value of M than to choose one of the alternate schemes. Their main purpose in this report is to illustrate sensitivity of results to station location and antenna design.

Table 4. The millimeter band system alternate schemes

Ground receiving system		$N_R^{1/2} D_R D_T$, ft²
Location	30-ft antenna	
Goldstone	Conventional	518
Goldstone	Advanced	469
7500-ft el	Assumed conventional	444
7500-ft el	Advanced	384

V. Description of a 10-μm Band (Carbon Dioxide) Laser System

The recently developed CO_2 laser system is the first laser that is capable of generating high power with moderate efficiency. This laser has all the desirable features of a gaseous-type laser; e.g., good frequency and amplitude stability, single-mode operation, etc. All other components necessary to construct an operational, medium-data-rate, deep-space communication system—such as modulators, image-tracking telescopes, and good detectors—are readily available. However, none of the necessary components has been space qualified.

The overall CO_2 laser communication system would closely resemble the existing microwave downlink system. This system consists of a frequency-stabilized spacecraft laser and modulator, a collimating telescope/antenna, a ground-receiving telescope/antenna, and a heterodyne detection system using a stable local laser/oscillator. Something that is possibly not needed for the microwave system (and very necessary for the laser system) is a closed-loop device to point the collimating telescope/antenna toward the earth. The microwave system has a good low-noise preamplifier for predetection amplification, but no such device is available for the CO_2 laser system.

The principal advantage of a laser system is the high antenna gain attainable with a moderate-sized collimating telescope. The spacecraft-borne telescope requires the additional hardware to aim it at the earth, however, resulting in increased spacecraft complexity. The main disadvantage is in the ground receiving part of the system. Heterodyne detection must be used, and system performance is materially affected by atmospheric effects. The nature of the detectors and filters available for use at 10.6 μm is such that a direct-detection system cannot be employed. Hence, superheterodyne detection is necessary to restrict the predetection bandwidth of the system. Furthermore, it is necessary to operate with high heterodyne-conversion gain, and this leads to questions of local oscillator amplitude stability. The wide variation of atmospheric turbulence effects with site selection poses a further problem for the receiving system.

The various parts for the CO_2 laser system are described in Subsections A and B. Subsection C discusses the effects of atmospheric turbulence and site selection, and Subsection D presents comments on cloud cover. Overall system performance is summarized in Subsection E.

A. Flight Hardware

A 10-μm data-transmission system for a spacecraft will have the following four basic parts:

(1) A laser master oscillator.

(2) A light modulator.

(3) A laser power amplifier.

(4) A collimating telescope and pointing system.

The CO_2 master oscillator and the pointing system are the most sensitive parts of the system. The oscillator frequency will undoubtedly be a function of environmental factors, such as temperature, etc. The oscillator will probably be a conventional laser consisting of a discharge tube and a two-mirror resonator constructed of low-expansion ceramic. As described, the frequency of the master oscillator will tend to drift if it is not stabilized by a closed-loop system. The problem with the frequency stability of a CO_2 laser is currently receiving considerable effort (Ref. 33). However, it is not yet certain what the long-term stability of such a system will be. Stability is required to enable the receiver to acquire and track the signal, and possibly, though not likely, to provide doppler-velocity data in addition to the microwave doppler. The CO_2 power amplifier is similar to the oscillator, with a discharge tube but without a resonant cavity, and will probably be constructed in a multiple-pass configuration to reduce its overall length.

Early CO_2 lasers in the laboratory were normally operated with their gas supply flowing slowly through the discharge tube rather than having a sealed-off, fixed charge of gas. Recently, CO_2 lasers have been fabricated (Refs. 34 and 35) that have a sealed discharge tube. These have been operated for more than 2000 h. The laser efficiencies are as high as 10% in single-mode operation. Research is currently being conducted on methods for improving their efficiency and lifetimes.

The modulator is the least-developed part of the transmission hardware. To the extent determined at the time of this study, only research models have been built. However, there is no serious doubt about the eventual development of the modulator.

The laser telescope and pointing subsystem is the most complex part of the system. Flight-engineered designs to date have been characterized by complexity, large f/D ratio (by microwave standards), and a resulting high weight-to-aperture ratio (Ref. 36). For this study, schemes are rejected that involve use of a telescope beamwidth less than the angular size of the earth (e.g., earth beacon schemes). These are unacceptably unreliable and operationally complex. Rather, a pointing system is demanded that employs a star tracker in which the earth is used as the star. Stabilization of the entire spacecraft to arc-second tolerances would not be required. The collimating telescope, mounted on stepping gimbals on a spacecraft with a conventional gas attitude-control system, would have a fine guiding system mounted near the telescope focal plane. The focal-plane image of the earth (and hence the direction of the outgoing laser beam) could be automatically controlled to arc-second accuracies (Refs. 37–39). The general direction of the gimbaled telescope can be controlled by open-loop commands from the spacecraft central computer and sequencer or by command via the microwave uplink in a manner similar to the Canopus tracker cone angle on the *Mariner* spacecraft. Velocity aberration and boresighting corrections, in the outgoing beam direction, can also be controlled by open-loop commands.

An intriguing possibility is to combine the earth tracker and transmission telescope optics. However, serious problems result from such an approach. Because of acquisition problems, and spacecraft attitude-control uncertainties, the earth tracker must have a field of view that is roughly 1 deg, whereas the transmission telescope will typically have a beamwidth of a few arc-seconds. In addition, the two systems differ in operating wavelength by an order of magnitude, and may have quite different aperture-size requirements. All of these factors tend to produce a combined-optics design that is characterized by a long focal length and attendant high weight.

An alternate approach would be to separate the earth-tracking function and provide two telescopes rigidly fastened together. However, it might be necessary to provide an additional vernier tracking capability in the transmission optics because of the difficulty of maintaining boresight of the two telescopes to the desired accuracy. It is clear that the designation of the telescope and pointing system will involve a complex set of trade-offs that have not been performed.

B. Description of Receiving Station

1. Telescope. The ground-based receiving telescope is not necessarily different from a conventional astronomical telescope, and would require a mirror whose optical quality is consistent with present technology. The choice of maximum telescope aperture is not based upon cost, but is determined by the atmospheric effects on the incoming signal. The maximum aperture over which the signal can be expected to be coherent is an extremely complicated function of local atmospheric conditions, and has not been measured at 10 μ. A theoretical estimate for the coherence diameter at 30-deg el angle is 1–2 m, and is based upon extrapolation of visible data to the infrared (Refs. 40–45).

Apertures larger than the coherent aperture can be achieved by adaptive arraying (Refs. 46–49), with the real possibility of using a large single primary mirror and appropriate optics to adaptively phase the signals from several smaller portions of the mirror.

The Perkin-Elmer Corporation, under contract to JPL, studied the design of a ground telescope for laser space communications at 10 μm. They recommend an azimuth–elevation mount for maximum rigidity and for high absolute pointing accuracy (see Ref. 45 and Refs. 50–51).

2. Atmosphere transmission and isotopes. The transparency of the earth's atmosphere at the CO_2 laser wavelengths is affected by the presence of CO_2 in the atmosphere.[8] Laboratory-measured absorption coefficients have been used (Ref. 52), and the average atmosphere transmission (straight up) due to atmospheric CO_2 has been calculated to be 71%. The rather obvious countermeasure is to shift the frequency of the lasers in both the transmitter and receiver by use of a rare isotope of CO_2. However, this does not solve the problem completely, as part of the loss is due to atmospheric water vapor.

The output of a CO_2 laser using the $C^{12}O^{18}$ isotope has already been examined (Refs. 53 and 54). The power levels were similar to those of the normal CO_2 laser. The wavelengths for the isotope $C^{13}O_2^{16}$ have been determined (Ref. 55), and a laser using $C^{14}O_2^{16}$ has been operated (Ref. 56). For atmospheric transmission, the band was compared to an atlas of the solar spectrum (Ref. 57), and it was found that the 9.5-μm ozone band makes the situation complex. The operating range of a laser using $C^{12}O_2^{18}$ falls within this range. However, both the isotopes $C^{13}O_2^{16}$ and $C^{14}O_2^{16}$ operate at wavelengths near 11 μm, and appear to be free of any atmospheric absorption lines.

The scattering effects of the atmosphere also affect the overall transmissions, but are not at all wavelength-sensitive, and cannot be as readily predicted.

3. Receiver. A typical optical receiver for CO_2 laser signals from a deep-space vehicle will consist of a large-aperture telescope, followed by optics to mix the incoming signal with the local oscillator (laser) signal, and finally a mixer/detector. The system lacks a preamplifier because of the large doppler shifts associated with typical spacecraft trajectories and the narrow tuning range of available molecular laser amplifiers.[9] Because the doppler shift precludes laser preamplification, it is necessary to rely entirely on optical heterodyne conversion gain. This imposes rather severe amplitude-stability requirements on the local oscillator.

An additional complication in using the optical receiver system is that of pointing the telescope to assure that the laser signal is focused on the detector and that its wavefront is aligned with the local laser wavefront. The pointing accuracy required (typically 1–2 s of arc) is such that open-loop pointing of the telescope will be relatively difficult. A real possibility exists that some sort of automatic closed-loop pointing system will be required. The lack of good preamplifiers and detectors complicates this problem because the closed-loop tracking system probably cannot depend upon arraying of heterodyne detectors.

A detailed design of an integrated tracking–receiving system does not exist at the present time, and will obviously require a great deal of work.

Several research groups have built CO_2 laser heterodyne receivers, primarily for the purpose of determining detector performance in the presence of large local-oscillator power levels (Refs. 58–61). The heterodyne

[8]The absorption is caused by thermal excitation (about 0.1% at 294°K) of exactly the same energy level (10°K at 1388 cm^{-1}) that serves as the terminal state in the laser emission.

[9]Eventually, frequency-shifting techniques may become efficient because there are strong nonlinear effects in appropriate materials. In this event, the shift may be applied at the transmitter to gain the advantages of a laser preamplifier in the receiver—especially its use as an image intensifier to aid in acquisition and tracking.

performance for a mercury doped germanium infrared detector at 10.6 μm is within 4 dB of the theoretical prediction, based upon quantum noise as the major noise source (see Ref. 60).

C. Site Selection

The main factors in the selection of tracking sites for 10-μm communications are the importance of good seeing and minimum cloud cover, both day and night. As mentioned previously, the usable telescope aperture will be limited by seeing rather than by the usual considerations of economics and surface tolerance. The phenomenon of seeing and its effect upon coherent optical reception have been studied in some detail (Refs. 62–67). However, for this report, it will suffice to estimate a coherent aperture diameter d by equating the diffraction-limited beamwidth, λ/d radian to the ordinary seeing blur circle that astronomers observe.

This procedure is conservative, as 10-μm seeing is probably somewhat better than visible seeing. Also, image tracking offers some improvement (equivalent to tilting the nominal wavefront to find a best fit to the actual random wavefront). If the seeing is accepted to be 2 s ($\approx$10 μrad), which is fair for night and very good for day then $d \approx 1$ m. The actual diameter D_R of the receiving telescope can exceed d and remain efficient if one resorts to the techniques of adaptive-phased arrays.

The complexity of multiple-phase adaptive receivers clearly puts a premium on selection of the best sites. Many of the good observatory sites are on mountain tops at fairly low altitude, where the air mass is not significantly less than one. The good seeing occurs at night because heat waves are not rising. Rather, the air is warmer than the ground and is settling down the mountain slopes. The good seeing on these lower peaks cannot be reasonably expected to persist during the day, at least not in all seasons, because the thermal balance will reverse, making the summit a source of rising heat waves. For continuous use, there is probably no substitute for a high-altitude site that leaves nearly half of the air mass and more than half of the water vapor out of the line of sight.

Two of the known observatory sites stand out: Mauna Kea, Hawaii, at 13,796 ft, and the northern part of the Chilean Andes.[10] The night seeing in both areas is frequently 0.5 s, but the day seeing apparently has never been measured. Mauna Kea has advantages. It is a part of the United States; there is no doubt which peak to use since there are only three and it is the highest; and it is developed for this purpose. Accessible peaks in the continental United States are just as high—e.g., White Mountain, Calif.—but the latitude is rather high and the weather is bad.

To choose a Chilean site, the surveys should extend northward into the Atacama Desert, where, at 23°S lat, one is now in progress. Astronomical surveys generally cut off at about 27°S lat because of the low elevation angle of interesting objects in the south polar sky. The limiting altitude for ground stations at developed sites is probably about 17,000 ft, where the air mass is slightly less than half. (This is the altitude of the cosmic-ray station on Mount Chacaltaya, Bolivia, but this particular spot may be too cloudy.) Figure 15 shows the hour-angle coverage that two stations, one in the Andes and one on Mauna Kea, would provide. The effective horizon is assumed to be 30 deg el. Neglecting the effects of latitude and declination, the coverage is 206 deg.[11]

D. Clouds

There is no doubt that clouds are among the main obstacles to optical communications. Seasonal maps of cloud cover have been made from data gathered by conventional means and by weather satellite. According to Landburg's cloud maps of the world, portions of the Sahara Desert are the only large areas that average as little as 10% cloud cover. Only a small area, about 200 mi west of the Red Sea, maintains this average during each season. Figure 16 was derived from Landburg's maps, and shows the only large areas of the earth that average less than 30% cloud cover each season (or, to be precise, less than 30% in each of six 2-mo periods). These areas are in North Africa, Arabia, and Australia. Australia is the only desirable area from the standpoints of logistics, ground communications, and geopolitics. The annual average cover for points within the Australian contours is typically about 20%.

[10]Jorgen Stock, a principal surveyor of Chilean sites, reported as follows: "Up to 2000 m (6500 ft) elevation, nighttime stratus is very frequent practically the year round. Above 2000 m, this effect is nonexistent. Over 3500 m (11,500 ft) convective clouds form during the summer season in the afternoon, but completely vanish at night. Presence of convective clouds depends very much on local topography and can essentially be avoided. Sites with a relatively easy access and with a local water supply can be found to well above 4000 m (13,000 ft). Of course, they will be remote from any center of civilization. Even so, for an infrared project, one should seriously consider going that high for obvious reasons."

[11]Unlike the Hawaii site, which has neither political nor logistic problems, the Chilean site must be regarded as primarily illustrative because of severe logistic and possible political difficulties.

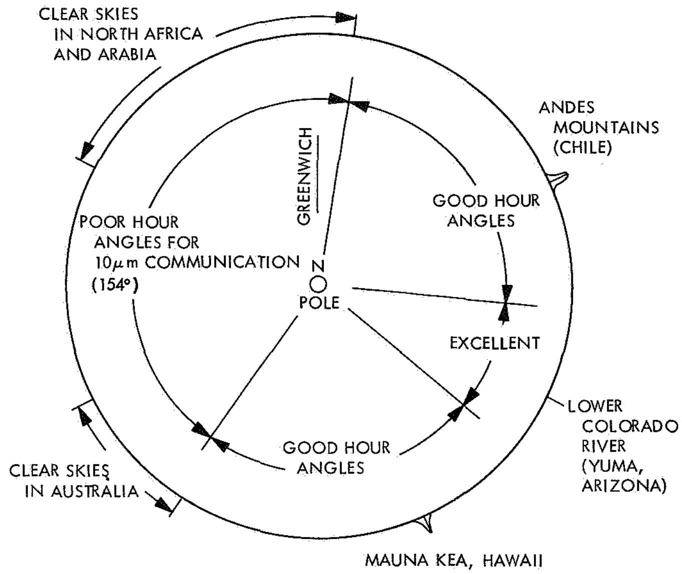

Fig. 15. Longitudes of possible optical sites

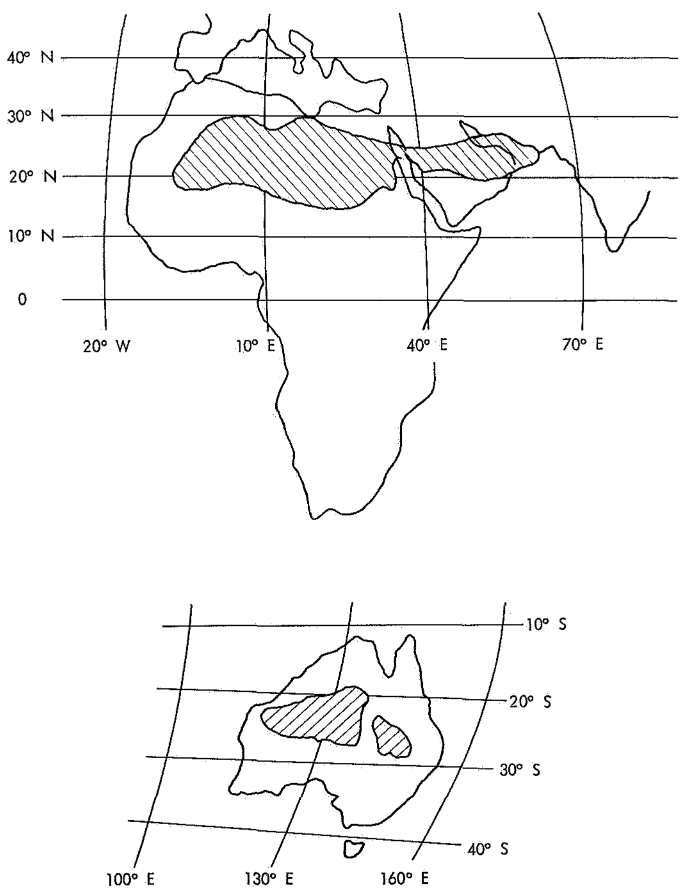

Fig. 16. Areas with less than 30% cloud cover each season

Because sites within the United States are preferred, the 30% cover criterion was relaxed to 40% (each season), providing an appreciable area of the southwestern United States. Figure 17 depicts this area as including the southern halves of Arizona and New Mexico plus bits of Texas and California. A small area at the mouth of the Colorado River averages less than 30% cloud cover each season.

The usefulness of these maps for the purpose of this report is limited because they do not resolve microclimates. Cerro Tololo, the site for the Inter-American observatory in Chile, reportedly has 330 good observing nights per year—more than that expected from the worldwide maps. The principal Hawaiian peaks are particularly important because they rise above most of the clouds, are accessible, are noted for superb seeing, and are in the United States. These peaks are Mauna Kea and Mauna Loa on Hawaii, each about 14,000 ft, and Haleakala on Maui, about 10,000 ft.

E. System Performance

Some of the efficiencies estimated for the 10-μm system may be in error by 20–50% of their values because of the difficulty of making predictions about a new technology. The efficiency of the CO_2 laser transmitter and the loss of coherence in the atmosphere are the most uncertain items. The assumption will be that the latter is a small effect, as the techniques of adaptive phased arrays can be used to combat the coherence loss.

In the subsequent paragraph, the transmission of both the atmosphere and the optics is assumed to be quite high. Most of the optics will be reflecting metal surfaces that have very low absorption in the mid-infrared. Whereas the transparency of the atmosphere in the

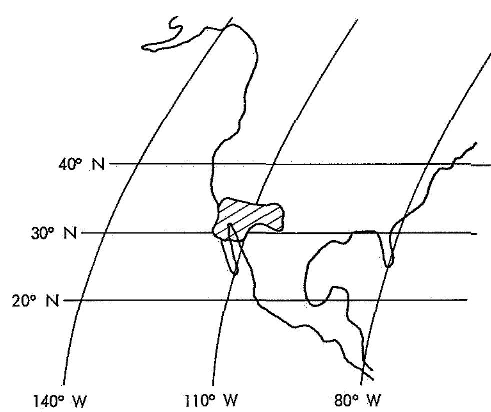

Fig. 17. Areas with less than 40% cloud cover each season

8–13-μm window is good at any altitude, it will be excellent at high-altitude observatory sites that are above most of the water vapor.

For the atmosphere, the transparency is assumed to be 85% and the efficiency due to loss of coherence, 90%. This means that the atmospheric efficiency would be 76.5%. The telescope efficiency, with unobscured aperture, would be 88%; transparency and reflectivity of optics, 82%; to give an optics efficiency of 72%. For the whole system, the efficiency estimates are: transmitter power conversion 12%, transmitter optics 72%, atmosphere 76.5%, receiver optics 72%, and detector quantum efficiency 40%. Therefore, η (system efficiency) equals 1.9%. Finally, the spectral density of quantum noise (the only appreciable source in a well-developed optical receiver) is

$$\Phi = hc/\lambda = 2.0 \times 10^{-20} \text{ W/Hz}$$

and Eq. (2) gives

$$N^{1/2} D_R D_T = 15.3 \text{ ft}^2$$

As with the microwave systems, no factors were included for loss of transmission time. Table 5 summarizes the CO_2 laser system parameters.

Table 5. The 10-μm band system performance parameters

Parameter	Value
Wavelength λ	10.59 μm
Receiving system noise spectral density Φ	2.0×10^{-20} W/Hz
Overall system efficiency η	1.9%
$N_R^{1/2} D_R D_T$ (for $M = 1.274 \times 10^{29}$ ft^2/J)	15.3 ft^2

VI. Description of a 0.87-μm (Gallium-Arsenide) Laser System

This section and Section VII present a discussion of laser communication systems in which the ground receiver uses direct detection rather than heterodyne detection. The direct-detection type of receiver has distinct advantages over the heterodyne-detection type. The antenna aperture can be larger because spatial coherence over the aperture is not required, and the lack of a local oscillator makes the optical design much simpler. However, in order to eliminate background-interference effects, a narrow-band predetection filter must be added. Because of the problems imposed by current filter technology, this filter limits the performance of the system. Furthermore, efficient low-noise detectors are not at present available for the near-infrared wavelengths.

The gallium-arsenide laser—a semiconductor type with an emitted wavelength of 0.87μm—has a reasonable efficiency (Table 6), and is relatively small and compact (Refs. 68–75). Present technology has produced single units capable of 3 W average power at 4% efficiency. Attempts are being made to produce phased arrays to obtain more power. The units are usually run in a pulsed mode, thus giving higher peak powers. The design of the spacecraft-borne transmitter antenna and pointing apparatus would be almost identical with that assumed in Section V, where the maximum aperture size is consistent with the beam-pointing assumptions (diam ~4 in. for a 2-s beam).

Table 6. System parameters for gallium-arsenide laser

Parameter	Value
Wavelength	0.87 μm
Component efficiencies	
Laser power conversion	4%
Transmitter optics and antenna	50%
Atmospheric transmission	85%
Receiver optics and antenna	50%
Narrow-band filter	30%
Advanced photodetector	30%
Overall system efficiency	0.0765%
System noise	4.56×10^{-19} J
$N^{1/2} D_R D_T$ (for $M = 1.274 \times 10^{29}$ ft^2/J)	31.7 ft^2

The receiving antenna would be of the *photon bucket* type (see Refs. 45, 50, and 51), and would have a very relaxed surface tolerance. Aperture diameters up to 30 ft having celestial sphere coverage may easily be attained. The remainder of the receiver consists of a predetection filter and a detector–amplifier combination.

The nature of the system noise spectral density at the receiver output terminals is somewhat involved. The system noise arises from three possible sources: (1) thermal effects in the detector–preamplifier, (2) background effects caused by sky noise or target-planet radiation, and (3) quantum-noise effects caused by the fundamental nature and wavelength of the radiation being used. Existing detectors are so designed that the detector thermal effects predominate, whereas the background and quantum effects are smaller and of comparable amplitude to each other. For this system to be considered, a significant advance must be made in near-infrared detectors. However, the trend toward better detectors has started (Refs. 76–79).

Hence, to make as favorable a comparison as possible with the CO_2 laser system, assuming that suitably advanced photodetectors and predetection filters are available, the system is quantum noise limited; thus, $\Phi = 2\ hc/\lambda = 4.566 \times 10^{-19}$ J at $\lambda = 0.87\ \mu$m.

For the receiver system, a rather high efficiency is assumed for the photodetector (30% vs 1% currently available). These assumed numbers are not unreasonably high, and will probably be attained in the near future. Table 6 summarizes the system parameters.

VII. Description of a 3.8-μm Laser System

Of the several atmospheric transmission windows in the visible and near infrared that could be used for optical communications (if the right lasers existed), the band from 3.5 to 4.1 μm might be the most desirable. The best features of this band are: (1) the potential availability of good low-noise detectors, and (2) the fact that background noise is minimum. Thus, an optical communication system operating in this band would not potentially be background-limited. The major difficulties are that efficient lasers do not exist for this wavelength and that infrared detectors for this band are not very efficient. However, the potential for making a good detector seems to be excellent. The quantum efficiency should easily approach 50%.

The basic configuration of the complete system would be identical to the direct-detection system described in Section VI. The system noise used for comparison purposes is again the limiting quantum noise. (The discussion in Section VI regarding noise applies equally here.)

The nature and configuration of a 3.8-μm laser is, of course, speculative. Recently, a new chemical laser (Ref. 80) was announced that operates in this wavelength range. It uses a flowing mixture of Freon and deuterium that is caused to react by a high-current pulse discharge. Although this laser is very inefficient, it is the first to

Table 7. System parameters for a hypothetical 3.8-μm laser system

Parameter	Value
Wavelength	3.8 μm
Component efficiencies	
Laser power conversion	10%
Transmitter optics and antenna	70%
Atmospheric transmission	90%
Receiver optics and antenna	60%
Narrow-band filter	50%
Advanced photodetector	40%
Overall system efficiency	0.75%
System noise	9.93×10^{-20} J
$N^{1/2}D_RD_T$ (for $M = 1.274 \times 10^{29}$ ft^2/J)	21.75 ft^2

oscillate near 3.8 μm, and requires further research to see if it can be made efficient. For the purposes of this comparison, 10% is chosen as a hopeful value of power-conversion efficiency for a hypothetical 3.8-μm laser. Table 7 presents a summary of the selected, representative system parameters.

VIII. Conclusions

This section will serve to compile and interpret the information generated in the previous sections, beginning with a presentation of the results derived for aperture sizes as a function of frequency band.

A. Aperture Sizes

In Section II, the bit-rate capability of all systems was defined to be exactly equal. Therefore, a possible choice between systems must be made solely on the basis of hardware attractiveness and growth potential. As one important parameter, the required aperture sizes have been investigated as a function of frequency band.

In previous sections, the noise spectral density Φ, the system efficiency η, and the aperture size product have been derived for each band. These figures are summarized in Table 8. In addition, a current weather-independent S-band system is included for comparison. In this connection, it is noted that the hard limits of Φ and η are nearly reached for S-band; thus, whether this system is called *current* or *circa 1975* is a minor point.

The data in the final column of Table 8 may be used to plot spacecraft aperture against ground aperture. Also,

Table 8. Summary of quantities that determine effective aperture product for six selected wavelengths

Band	Wavelength, λ	Noise, °K	Efficiency η, %	$N_R^{1/2} D_R D_T$,[c] ft²
S[a]	13 cm	20.56	10.6	8130
X[b]	3.55 cm	22.41	11.0	2780
mm[b]	3.33 mm	71.0	9.0	518
CO_2[b]	10.59 μm	1,470	2.3	13.8
GaAs[b]	0.85 μm	33,700	0.0765	31.7
—[b]	3.8 μm	7,340	0.75	21.8

[a]Current system.
[b]Circa 1975.
[c]$M = 1.274 \times 10^{29}$ ft²/J.

the parameters for frequency band are shown. The information was used to develop Fig. 18.

Some maximum transmitter aperture sizes—called "Mars limit," "Jupiter limit," and "1 arc sec limit"—are marked on the laser plots in Fig. 18. These limits apply to the spacecraft transmitting antenna, and occur where the required precision for pointing the transmitted beam reaches the limit for reasonable ease and reliability. Briefly, the limiting aperture makes a beam angle ($1.22\ \lambda/D_T$) rad equal to that subtended by the radius of the earth as seen from the target planet, or 1 arc sec, whichever is larger. The former corresponds to illuminating one quarter of the earth's disc (projected area) from a Mars encounter range (2.3 AU). As a result of this constraint on spacecraft antenna gain, the ground-aperture requirement appears to decrease with range. This is because performance is measured relative to systems that depend upon range in the normal way.

So far, a single set of numbers has been derived for the characterization of weather-dependent wavelengths; namely, the aperture sizes required to perform a communication task of standardized difficulty. The equipment characteristics are identified in the subsequent paragraphs as a function of frequency band. Further, an attempt is made to illuminate the advantages and disadvantages of each band.

B. System Characteristics vs Frequency Band

This subsection provides an explanation and interpretation of Fig. 19. Starting at the left of this figure, the system need is axiomatically established. Then a family of high-risk solutions is quickly dismissed as being beyond the scope of this study. (However, such solutions may prevail in the distant future.)

As indicated in the introduction (Section I), S-band is a stable, mature approach to interplanetary communications that can optimally support most of the standard functions of command, precision doppler, engineering telemetry, and scientific medium-rate data. Therefore, no reason exists for replacement of S-band by more exotic approaches for these purposes (any more than automobiles can be replaced by aircraft). On the other hand, existing S-band systems are approaching data-rate limits for specified spacecraft power/weight values. In addition, a significant S-band limitation exists because of available bandwidth allocations. Large ground antenna arrays are economically discouraging (see Ref. 1), and spacecraft antennas that are large, compared to the spacecraft structure size, impose a serious design problem because the entire spacecraft design is grossly determined and possibly jeopardized by the antenna.[12]

From an implementation point of view, the next easiest solution after S-band is X-band. The technology is advanced, and the S-band antennas (ground and spacecraft) may be used (perhaps simultaneously). Much of the ground receiving equipment is usable, and much of the spacecraft transmitter technology is applicable. However, hard limits constrain X-band growth at a data rate that is about 10 times (the frequency ratio squared) that which is practical with S-band. With an eye to the future, it is necessary to look even higher in frequency.

The utility of the millimeter band is hard to interpret because the performance depends critically upon the receiver front end, a component that is poorly developed. One major factor makes this band an interesting alternate to X-band. The millimeter-band ground antenna is small, having the practical effect of making development more flexible, perhaps less costly, and more amenable to arraying approaches.

A second consideration of some significance is that (unlike X-band) man-made interference is not a problem. For the time being, the millimeter band must be regarded

[12]The applicable philosophy is sharply different for earth-orbit (including synchronous) missions. Launch-window restrictions are less severe, the program schedule is not inflexible, the launch-to-experiment time is in days rather than months, experiments are subjected to less critical review, the tracking network involvement is simpler, and the payload is larger for a given booster. The *Applications Technology Satellite* program has recognized these considerations by investigating innovations that would not be reasonable on an interplanetary mission. For example: a CO_2 laser communication experiment is being planned for ATS-F and -G in 1972–1973.

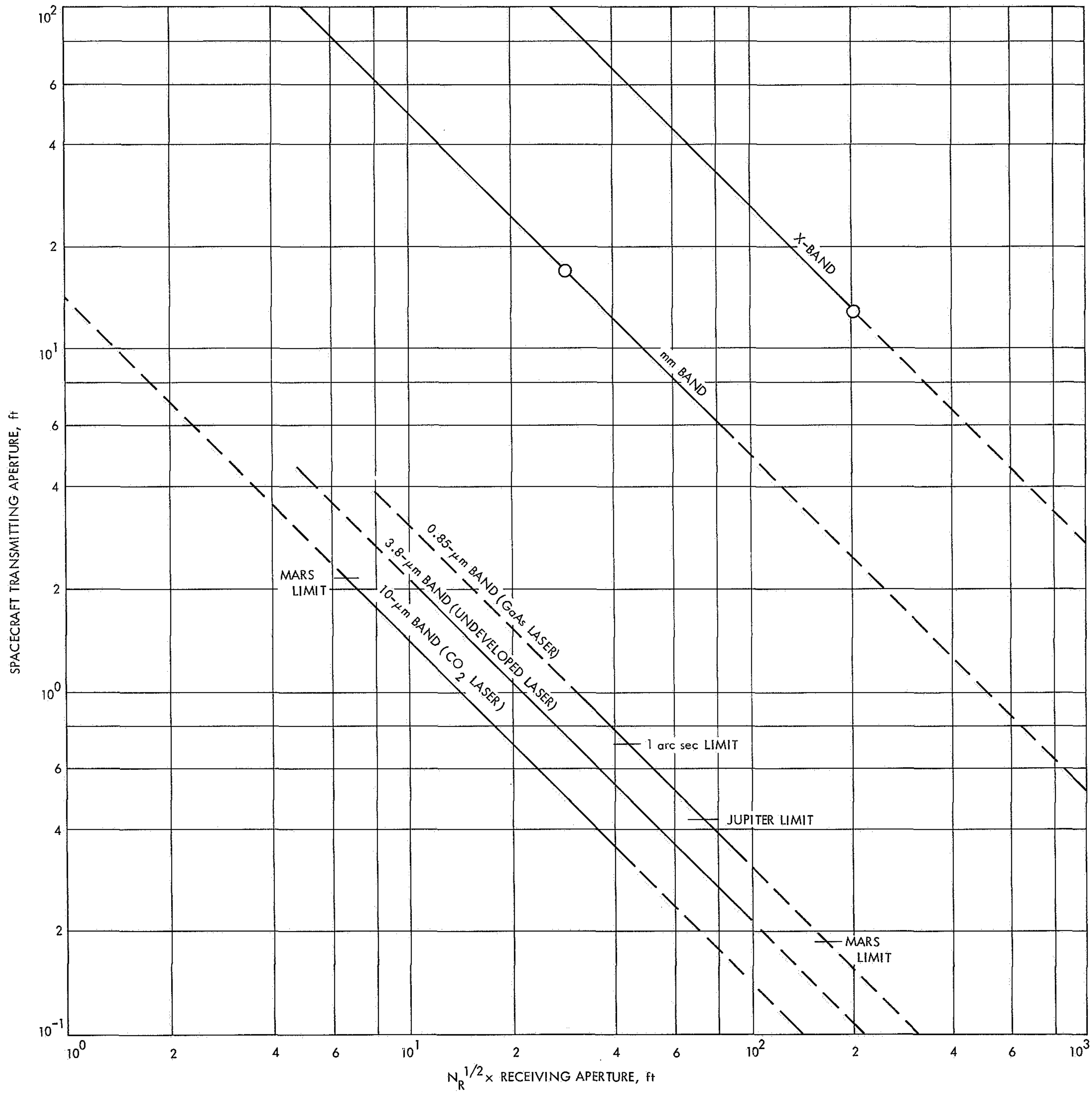

Fig. 18. Spacecraft and ground aperture sizes to provide selected capability

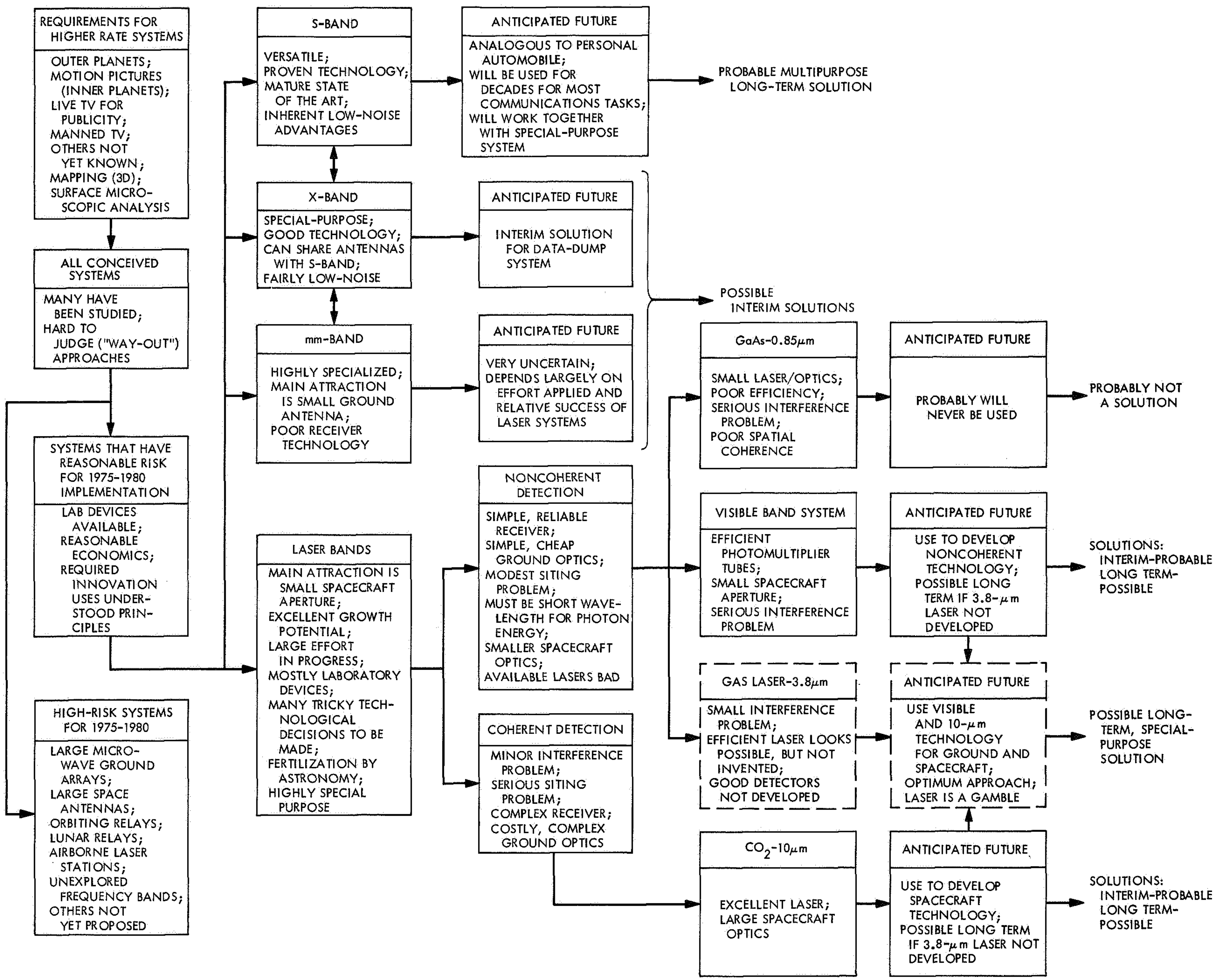

Fig. 19. High-data-rate system evolution

largely as a question mark. However, for the M value (see Section II-B) selected in this report, the X-band system has close to the largest practical ground antenna and a marginally reasonable spacecraft antenna size. The millimeter system still has growth potential, however, in terms of ground-antenna aperture (see Section IV-C).

In the laser bands, it is possible to have a very large spacecraft antenna gain with a modest-sized aperture. Unfortunately, the receiver noise spectral density is fundamentally two to three orders of magnitude worse than in the microwave bands. In addition, this involves a more sophisticated spacecraft antenna-pointing system and a less attractive ground-station seeing situation. Finally, the laser system is highly special purpose, and nonadaptable (even in good weather) to such requirements as precision doppler and command links. The result of these conflicting considerations, taken together with a new and rapidly advancing technology, is that judgments are difficult.

Classical astronomy has traditionally used incoherent (power) detection of energy that has been concentrated by a large quasiparabolic reflector. Combined problems of surface accuracy and atmospheric turbulence generally preclude diffraction-limited operation, which is not necessary with this detection method. For space communications, the obvious attractiveness of a simple, reliable receiver, relaxed ground telescope surface-accuracy requirements, and satisfactory seeing at sites within the continental United States has led to a concerted effort to design laser communications systems around this type of detection. Since power detection is more feasible for the shorter wavelengths (less than 1 μ at present), smaller and lighter spacecraft apertures result. Unfortunately, two serious problems exist. The more fundamental problem is that interference from sky and planetary blackbody noise may be large compared to quantum noise for foreseeable information bandwidths. The second problem is that laser types available at present have poor efficiency.

The availability of the high-efficiency CO_2-N_2 gas laser in the 10-μm band has stimulated active consideration of superheterodyne detection schemes for laser communications. The atmosphere is quite transparent in this band, and the wavelength is about 20 times that normally investigated in astronomy; this makes diffraction-limited, ground-aperture operation more feasible. The sensitivity-limiting quantum noise (which is proportional to frequency) is also 20 times smaller, yet the wavelength is still sufficiently short that maximum spacecraft aperture for reliable pointing is conveniently sized (1–2 ft). Finally, all of the necessary parts for an interplanetary data link are available in prototype research laboratory form. The two major problems with a 10-μm system are the complexity of the superheterodyne receiving equipment and the extreme system sensitivity to atmospheric turbulence. The latter consideration forces possibly undesirable countermeasures, such as logistically poor site location, adaptive aperture arraying, airborne stations (see Appendix A), or some combination of these.

A possible future solution to the dilemma outlined in the preceding two paragraphs lies in the 3.8-μm band. In this band, the atmosphere is exceedingly transparent and both atmospheric and planetary noise are reasonably small. Although not yet invented, a high-efficiency gas laser using an analogous interaction scheme to that in the CO_2-N_2 laser appears possible. Also, the appearance of such a device would no doubt stimulate detector technology in this band to produce a usable detection device. The hypothetical 3.8-μm system would have spacecraft equipment closely resembling that required for the 10-μm system. On the other hand, the power-detecting ground receiving system might closely resemble that required for the 0.85-μm system (Section VI).

Each of the frequency bands analyzed in this report (X-band, millimeter band, 10 μm, 0.85 μm, and 3.8 μm) has attractive features and serious problems. Choices between these bands must be made with caution. The subsequent paragraphs list a set of recommendations for further investigation.

C. Suggested Lines of Research

To use higher frequency bands, links must be used that are somewhat weather-dependent. The only links that can accept this weather-dependency are those using the high-rate data-dump technique. The performance characteristics of these high-rate data links are relatively independent of frequency band, although the equipment characteristics are not. The S-band system is a necessary adjunct to this high-rate link, not only to perform other required weather-independent functions but to provide a reliable command uplink and a reliable engineering telemetry link for the data-dump system.

It appears that there is no data-dump frequency band that has good growth potential and can be easily used. Serious but apparently solvable problems exist in each band. In this subsection, the work is noted that is required to alleviate and—it is hoped—solve these problems. In making these recommendations, no identity is provided as to where the work is done or the sponsor.

1. Modulation/detection theory. The high level of technology in this field should be applied to the systems described in this report. In particular, the best signal waveforms for a power detection (nonheterodyne) system should be developed. These, in turn, should be compared with waveforms for appropriate heterodyne systems so that a clearer understanding of relative system attractiveness may evolve.

2. Bulk data storage. Interplanetary spacecraft with data storage of enormous capacity have been established in this report as a requirement. For typical minor-planet situations and typical weather outages, capacities of 10^{10}–10^{12} bits are required. This implies photographic or even more exotic techniques. Additional consideration should be given to the mechanics of bit storage, e.g., whether it is necessary or desirable to store the information in baseband forms or whether it is attractive to consider schemes for more direct storage and playback.

3. Data-dump system design. The type of data-dump system proposed in this report should be brought into clearer focus. This type of system should be analyzed for sample missions and from an operations point of view. Of particular interest are the propagation-time-delay problem described in Section II-B (see Table 1) and the weather-dependent station-maintenance concept proposed in Section III-C.

4. Weather-dependent microwave systems. For the millimeter band, techniques should be investigated for precision antennas of 30–60 ft size range. In particular, it has been noted that the Hale telescope at Mount Palomar is of a 17-ft aperture, accurate to a few millionths of an inch, and that the cost of such reflectors could be reduced by less-stringent surface requirements.

Spacecraft power amplifier and power supply design should be stimulated to provide more flightworthy devices than those that exist in these bands at present. Techniques for lightweight, reliable spacecraft antennas should be developed, together with techniques for antenna pointing.

Activity in the area of millimeter-band, low-noise receivers should be stimulated. Laboratory devices should be field tested in some type of two-way system, perhaps lunar or planetary radar systems. This would not only ultimately provide reliable, high-performance components, but would provide familiarity with such system considerations as weather effects. Additionally, data of scientific merit might result.

5. Laser systems. As a problem common to all laser systems, the area of spacecraft telescope pointing and design should be emphasized from a flight hardware point of view. The goal should be a reliable, lightweight package that is modestly sized in all dimensions (no long telescope tubes) and can conveniently solve acquisition problems. This package should be conceived as a device that can be placed aboard a spacecraft without grossly affecting either the spacecraft configuration or its attitude-control system design. If these requirements cannot be met, a hypothetical laser system loses attractiveness, there being no other feature of laser systems that is attractive when compared with microwave systems. Therefore, the laser spacecraft aperture-pointing system should not be a modified, scaled-down version of classical ground telescope designs; rather, it involves a configuration departure to satisfy a different set of requirements.

The gas laser is the most attractive spacecraft transmitter (barring presently unconceived types). At the present time, the choice is further narrowed to the CO_2-N_2 10-μm device. Extensive effort should be applied to space-qualify this item, particularly in the areas of ruggedization, sealed-off operation, isotopic modification, compactness, and thermal or frequency stability. In addition, the optical link between the laser amplifier and the telescope should be studied. Consideration should be given to the desirability of—and techniques for—avoiding laser gimbaling.

Research to develop an efficient 3.8-μm gas laser should be actively stimulated. If and when such a device is developed, high-efficiency quantum-counter and modulator technology should be vigorously pursued.

Activity with short-wavelength lasers (e.g., gallium arsenide types) should be continued at a modest level, primarily in anticipation that a nonheterodyne 3.8-μm system may come into being someday. In this event, siting considerations, system design, modulation/detection schemes, receiver design, and ground telescope design (possibly segmented optics) will all be generally applicable to the 3.8-μm system.

Activity to develop a fieldworthy 10-μm heterodyne receiver should be vigorously pursued for two principal reasons. Primarily, a gas-laser package should be flown as soon as practicable—and a receiver is required for such an experiment. This experiment should not wait for the possible development of a 3.8-μm gas laser. Secondly, the receiver is desirable (if not necessary) to perform laboratory tests on the spacecraft package, and to make more definite present knowledge of atmospheric effects.

Because of the uncertainty of the long-range future for heterodyne detection, two types of ground telescope design should be investigated. One is semiclassical, with possible subaperture arraying; the other is some economically optimal approach to large incoherent optical apertures (possibly segmented optics).

Siting studies should be approached with extreme caution. Preliminary space experiments should use existing or approved astronomical facilities. Siting studies for possible future power-detection laser systems should emphasize good seeing, together with logistic convenience. Siting studies for future heterodyne detection systems (10 μm, for example) should emphasize superb seeing at the expense of logistics. Possible all-purpose siting solutions exist in the islands of Hawaii and Maui, as discussed previously.

The possibility of laser types other than those discussed in the previous portion of this report is presented in Appendix B, with the emphasis placed upon other types of power sources.

As a final comment, very serious attention should be given to better cooperation between optical communications and astronomy (see Appendix C). Radio astronomy is a close historical analogy in which initial space communications systems made use of radio-telescope designs and techniques. In those early days, radio astronomers could see little benefit to them in space communications. More recently, however, they have begun to use such NASA-developed techniques as masers, high-performance antenna feeds, and data processing techniques. The present situation is one of information exchange, partial sharing of facilities, general cooperation, and mutual respect.

Appendix A

Airborne Lighter-Than-Air Earth Stations

The CO_2 system could use a telescope light enough for use in flight, although it would require special lightweight construction similar to that of telescopes in the Orbiting Astronomical Observatory or *Stratoscope*. Lunar eclipse measurements (Ref. 81) have established some precedent, but with much smaller telescopes. A 70- to 100-in. telescope cannot be used to look out through a practical window or dome, especially at a wavelength beyond the cutoff of glass and quartz. Also, the telescope will not operate satisfactorily in high wind. These and other factors preclude the use of conventional aircraft, and focus attention on lighter-than-air craft.

The *Stratoscope* project has established precedent for lifting moderately large optics to high altitude; for reliable communication, however, the uncontrolled weather-dependent launch and recovery situations could not be tolerated. A powered, steerable airship would be required that is seldom, if ever, grounded by weather. Airships have been used as radomes, which is another precedent of sorts. One manufacturer (Goodyear) indicates that various types of dirigibles and medium-to-large blimps have sufficient lift and altitude (several tons to 10,000 ft), and have adequate crusing range. During World War II, they operated in winds up to 50 knots. Unfortunately, few such airships are in operation now, and the type required is likely to be of a special design.

For the telescope to look out the top, the central portion might have to be rigid like a zeppelin and slotted like the dome of an observatory. The remainder of the structure and the engine designs could compromise streamlined shape and speed in favor of greater altitude and lift. The net effect might be a hybrid between zeppelin, blimp, and high-altitude balloon. If necessary during tracking, the ship's heading could be nearly determined by the target azimuth, and the engines could maintain just enough speed for steerageway. Guide stars would be required during target acquisition. An advantage of this unorthodox scheme would be the ability to select in advance an optimum base of operation for a particular event. The choice could depend upon encounter time, political climate, and probable weather.

Although American-built zeppelins (*Akron, Macon,* and *Shenandoah*) are mainly remembered for their disasters, it should be noted that the German design fared much better (with the exception of the *Hindenburg*, which could not have burned had it been filled with helium). The *Graf Zeppelin, Los Angeles,* and others established an excellent safety record, much of it in regular passenger service. The American blimps established good safety records during World War II. In one postwar exercise, they even operated while other military and commercial aircraft were grounded by weather.

Appendix B

Sun-Pumped and Chemical Lasers

A number of laboratories have already demonstrated the feasibility of pumping lasers with focused sunlight. A system based on YAG:Nd^{3+} (yttrium aluminum garnet doped with trivalent neodymium) that delivers 1 W at 1.06 μ when excited with sunlight (October, 42 deg N lat) from a 2-ft collector was reported in Ref. 82. In this report, it is predicted that a 1-ft collector would suffice in a space environment, with certain foreseeable improvements in the system.

For space applications, sun pumping offers the possibility of bypassing the solar panel to gain increased communications power efficiency. The potential increase is considerable because the efficiency of solar-power conversion is only about 10%. Unfortunately, this possibility does not apply to the outer planets—from which the communications problem is most severe. So far, the laser efficiencies demonstrated have not been sufficient to warrant including these lasers in the present calculations, based on the range equation. If and when they are included, the comparison will require some detail about the spacecraft and its mission.

The system could be so arranged that the parts of the solar spectrum that do not pump the laser are salvaged for other purposes. The front surface of a transparent collector could be coated to reflect only those colors that excite the laser; the remainder of the sunlight could pass through to a solar panel on the back of the collector. Obviously, this arrangement complicates estimates of communications power efficiency, as the question involves other spacecraft power requirements and spectral overlap of useful absorption bands in lasers and solar cells. Moreover, substituting collector optics for part or all of the solar panel involves significant changes in spacecraft design. This is especially the case because either the sunlight or the laser output must be reflected from a direction that depends upon the sun's position to one that depends upon that of the earth—an angular relationship that varies with time.

The YAG:Nd laser noted above is an example of the crystalline class of light-pumped lasers in which impurity ions Nd^{3+} are excited directly by light absorption. Recently, a remarkable laser performance was demonstrated (Ref. 83) with a variation of the nodymium ion type that undoubtedly will be developed into sun-pumped form. This laser also radiates at 10.6 μ, but the ion is dissolved in liquid selenium oxychloride instead of a solid host. Further research with this type should develop some very interesting power levels, efficiencies, and other performance data.

Another class of light-pumped laser, less developed but possibly more attractive for communication, is a gas laser in which the gas breaks down by photodissociation, leaving molecular fragments in a suitably excited state for laser action (Refs. 84 and 85).

This scheme is not restricted to the short wavelengths in which solid-state lasers operate. Broadband absorption is assured because excess photon energy can go into kinetic energy of fragments. One problem is finding a photodissociation from which the fragments combine to regenerate the original gas. (Other recombination products are tolerable only if they also photodissociate or otherwise react so that an appreciable amount of the original gas is present in chemical equilibrium.)

For the most part, it has been tacitly assumed that the usual situation prevails in which spacecraft power rather than energy is the quantity in limited supply; that is, data can be stored aboard a spacecraft, but not the energy with which to transmit data. Obviously, a fair-weather optical system that employs spacecraft data storage and bulk data dumping would be better adapted to the energy limitation, and would consume it rapidly during best seeing conditions. The energy limit is possible with a chemical laser, and is rather attractive for outer planets, where sunlight is a poor source of power.

Chemical lasers are powered directly by gaseous fuels that react to form a product in an appropriate excited state for laser action. So far, they have not been very successful; therefore, they shall not be discussed in detail, but some orders of magnitude will merely be noted. There are 6.025×10^{26} molecules in a kilogram-mole of fuel. Therefore, as many as 10^{25} photons of laser light may be available from a fair-sized mass of fuel if a laser having reasonable quantum efficiency is developed. If a 4 arc sec beam were aimed at a 120-in. ground telescope, then 1 photon in 25×10^{12} would be received from Jupiter, or 1 in 83×10^{12} from Saturn. Allowing 100 photons per bit of information encoded, this suffices to transmit 3.9 or 1.2-Gbits. At about 10^6 bits per frame, it may be possible to transmit thousands of pictures in this manner.

Appendix C

By-products of the NASA Astronomy Program

The problems of atmosphere and beam pointing are significantly alleviated by the NASA astronomy program, which is independently solving some of the most serious problems.

Most important for a possible optical link is the development of techniques for precision pointing from vehicles. The distinction between pointing for the purpose of viewing and pointing for laser transmission is not essential because of the reciprocity of light rays. The pointing of the orbiting astronomical observatory is a problem very similar to that of laser pointing (see Ref. 38).

Recent *Stratoscope II* flights have succeeded in pointing telescopes to about 1 arc sec (see Refs. 39 and 40 and Ref. 86) in a windy environment that is probably less stable than that of any unmanned spacecraft. This was done without the fine guidance system that is expected to operate in the next flight. Also, programs that employ suborbital rocket flights (sounding rockets) for astronomical observations in vacuum ultraviolet and other absorbed bands require increased pointing precision.

A second but more remote possibility for future coordination between space astronomy and laser communications is the opportunity to share one or more large orbital telescopes (LOT).[13] Such a telescope, successfully used as a relay, would solve all of the atmospheric problems, and would also eliminate the need for stations spaced every 120 deg of longitude for full zodiac coverage. The line of sight from a spacecraft to a LOT relay in high orbit (say, synchronous) would seldom if ever be interrupted by the earth (see Ref. 36). Apart from weight allocation, the design of a LOT as an astronomical instrument need not be compromised to include a communications package. The latter would be only one of several different interchangeable detectors and experiment packages that would have to be positioned at a focal point on command from the remote astronomer or communicator.

Nevertheless, the prospect of mixing communications with orbital astronomy raises serious questions of cost effectiveness. Time on the telescope would be so valuable that it is doubtful whether it should ever be used for a function that can be performed from the ground or by other means.

Other kinds of coordination between astronomy and communications may be listed, but are highly speculative because it is not known whether they have been systematically studied. A Saturn flyby that carries a medium-sized (9–30 in.) telescope for communications may be considered as an example. After encounter, when the closeup pictures and other data have all been transmitted, a telescope will be available for viewing the solar system from a most unique position. Of the various possible observations, some can be arranged without significantly compromising the communications design. The first such use could be continued observation of the target planet and its satellites. As these recede from the spacecraft, there will be months during which resolution with medium aperture from the spacecraft would far exceed the resolution with a LOT.

Another target might be dust—i.e., zodiacal light-scattering material (Ref. 91)—in the inner solar system. The advantage of observing this from a distance may be compared to the advantage of being outside of a thin cloud while estimating its shape and extent.

Miscellaneous uses might include astrometrical observations of planets against the star field when the unique observation angle helps to reduce ephemeris errors.

[13]For astronomy, the LOT provides four important advantages: (1) Its view of the universe includes the vacuum ultraviolet, far infrared, and other bands that are totally absorbed by the atmosphere; these bands are likely to hold clues that will alter man's concept of the universe. (2) Its angular resolution is limited only by the diffraction angle of the aperture and the precision of its optics. The best seeing obtainable in the atmosphere (about 0.5 s arc) corresponds to the diffraction limit of green light through an aperture of only 8 in. whereas good seeing at the principal observatory sites (about 2 s) corresponds to only 2 in. with green light. (3) The LOT removes the airglow limitation from astronomy. This advantage allows detection of fainter objects by longer exposure of photographic plates (or other integrating image devices) before the background limit is reached. (4) The LOT would be a 24-h/day observatory, as compared to only about 8 h/day average for a ground observatory.

The acronym LOT was suggested by the Space Science Board of the National Academy of Sciences (Ref. 87). The board strongly recommended proceeding with a LOT program, suggesting a high orbit, an aperture of 120 in. or more, and a launch date *circa* 1979. Similar telescopes with other acronyms—e.g., MOT: manned orbiting telescope (Refs. 88–90)—have been proposed, and are being studied.

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