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PARAMETRIC ANALYSIS OF MICROWAVE AND LASER SYSTEMS FOR COMMUNICATION AND TRACKING

Volume I - Summary

Prepared by
HUGHES AIRCRAFT COMPANY
Culver City, Calif. 90230
for Goddard Space Flight Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1970

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16. Abstract

Present and future space programs are requiring progressively higher communication rates. For instance, the Earth Resources Technology Satellite-A requires about 70 MHz total bandwidth in its S-Band downlink spectra, and it appears likely that future earth observation satellites will require more bandwidth because of the larger number of sensors and higher sensor resolutions. On the other hand, the frequency bands allocated via international agreements for space use are limited, and hence, the r-f spectrum is becoming crowded. However, the advent of the C-W laser systems offered a "new" and wide electromagnetic spectrum for use in space telecommunications. Although the laser systems offered this "new" capability, their technological development was also new. Therefore, this study was undertaken to make a comparative analysis of microwave and laser space telecommunication systems. A fundamental objective of the study was to provide the mission planner and designer with reference data (weight, volume, reliability, and costs), supplementary material, and a trade-off methodology for selecting the system (microwave or optical) which best suits his requirements. This report is the final report of that study. Because of the large amount of material, the report is presented in four volumes. This volume, Volume I - Summary, summarizes the: (1) significant results of the study program; (2) estimated best use for laser and microwave communications; (3) "Reference Data for Advanced Space Communication and Tracking Systems; (4) design criteria and trade-off methodology developed to select the best system for a given mission; and (5) future ground stations for space communications.

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PARAMETRIC ANALYSIS OF MICROWAVE AND LASER SYSTEMS FOR COMMUNICATION AND TRACKING

VOLUME I	**SUMMARY**
VOLUME II	SYSTEM SELECTION
VOLUME III	REFERENCE DATA FOR ADVANCED SPACE COMMUNICATION AND TRACKING SYSTEMS
VOLUME IV	OPERATIONAL ENVIRONMENT AND SYSTEM IMPLEMENTATION

DETAILED INDEX OF VOLUME I

BRIEF INDEX OF VOLUME I

INTRODUCTION

Contract goals are presented in summary form. The organization of the Summary Volume and the entire Final Report is also noted.

Contract Goals

Contract NAS 5-9637, "Parametric Analysis of Microwave and Laser Systems for Communication and Tracking" had four general goals. The first goal was to examine microwave and laser communications systems to determine the feasibility of laser communication for space and to determine those space missions best suited for laser communication and for microwave communication.

The second goal was to perform system tradeoff studies of the various technologies that are pertinent to microwave and laser communications. From these a "Reference Data for Advanced Space Communication and Tracking Systems" was to be developed.

Thirdly, a design criteria was to be developed for laser and microwave systems which could determine the best system to use, based upon agreed criteria. The criteria was to be flexible allowing comparisons to be made on present hardware capabilities and upon projected future capabilities.

Fourthly, an implementation plan was to be provided to integrate future laser and microwave ground systems into present and future world wide systems.

Summary Format

Following this introduction, this Summary Volume has five sections: 1) A summary of significant program results, 2) a summary of the estimated best use for laser and microwave communications, 3) a summary of the "Reference Data for Advanced Space Communication and Tracking Systems," 4) a summary of the design criteria developed to select the best system for a given mission, and 5) a summary of future ground stations for space communications.

Final Report Format

The final report for NAS 5-9637 is in four volumes. The first volume is this summary volume with the format noted above. The second volume is entitled "System Selection" and contains two major parts, "Mission Analysis and Methodology" and "System Theory." The first part is a review of mission constraints, history and plans. It is given as a foundation for understanding space communication goals. The methodology or design criteria developed under this contract is also described in this part and in pertinent appendices.

"System Theory" describes the constraining equations used to determine deep space communications link performance. Special treatment is given to the determination of signal to noise ratios in optical communications systems.

Volume III is the "Reference Data for Advanced Space Communication and Tracking Systems." It contains theory and state-of-the-art performance for the following technology areas for both microwave and laser frequencies: transmitting power sources, modulators, detectors, transmitting and receiving apertures, acquisition and tracking, and prime power and heat rejection systems.

Volume IV is entitled "Operational Environment and System Implementation." It has three major parts: Background Radiation and Atmospheric Propagation, Ground Receiving Facilities, and System Implementation.

Background Radiation and Atmospheric Propagation deals with interfering signals that compete with both laser and microwave communication. Further the atmospheric attenuation as a function of frequency and weather condition is given.

The ground receiving facilities part contains a brief description of current world wide networks such as the DSIF and STADAN.

System Implementation describes the communications systems of several successful spacecraft. These may be used as a reference and comparison for future design.

SUMMARY OF SIGNIFICANT RESULTS

Significant contractual results are the production of a Reference Data for space communication and a workable Design Criteria for selecting optimum communications systems.

Introduction

The significance of the results of NAS 5-9637 lies not in the solution to a particular problem but in the assembling of facts and the development of a means to solve several classes of communications system problems in an optimum way. This general result is framed within the guidelines and bounds of the statement of work noted briefly in the previous topic. Such a result extends the usefulness of the study beyond the scope of immediate comparisons to aid in the planning and guidance of communication systems parameter selection for future missions.

The general result mentioned in the previous paragraph is built upon the two-fold foundation of a communications methodology or design criteria and a reference data summary. From this fundamental yet flexible base, it is possible to make a wide variety of comparisons each of which may be easily fitted to the particular problem and constraints of the user. The following paragraphs present some of the specific results of this general contractual result.

Laser/Microwave Usage

An important question to be answered by the study was that of determining those missions where laser communication, microwave communication, and hybrid microwave and laser systems were superior. The answer to this question depends upon the demands made upon the link. if high demands (long range, high data rate,* and large amounts of data) are made on the link, laser systems can be designed which are both lighter and less expensive than microwave systems. A mission that could profitably use a laser communication system would be a photographic reconnaissance vehicle orbiting Mars.

If the demands made upon the communication link are not large, then a radio link is superior from the standpoint of weight and cost.

Hybrid systems find two general applications. First, a hybrid system may be used to overcome atmospheric effects. The implementation here is a laser link from a deep space probe to an orbiting relay satellite and a radio link from the orbiting satellite to earth. The second general application of hybrid systems is that of simultaneously using a radio and an optical link from a spacecraft. Indeed this may well be the standard configuration of the "laser" link, since the radio link will be used for lowdata rate housekeeping data and for tracking while the laser link will be used for wide band data transmission.

*High data rate is taken as greater than 10^6 bits/sec. Low data rate is taken as less than 100 bits/sec. Medium data rate is between these approximate values.

Reference Data Summary

The reference data consists of a description of technology theory and practice pertinent to deep space communication. These areas include: transmitting power sources, modulators, detectors, transmitting and receiving apertures, acquisition and tracking, prime power sources, and heat rejection systems. For each of these technologies, relationships were developed which relates the parameter values to its weight and cost. The weight and cost relationships were then used in the implementation of the design criteria to determine the set of parameter values which produced the system which is lightest or least expensive overall.

Design Criteria

The purpose of the design criteria is to provide a means of determining the best communications system implementation.

The criteria includes comparisons of systems and includes the determination of the best communication system parameters values for a particular system and set of constraints. Two criteria are used, weight and cost. Thus microwave and laser system may be compared on either of these criteria, and when compared, each has parameters selected such that each type of system is the lightest or least expensive based upon the reference data.

The design criteria has been implemented as a computer program during this contract and has the mnemonic name of COPS (Communications Optimization Program with Stops).

Future Ground System Implementation

The current status of world wide systems includes several world wide radio systems but no optical systems. For that reason only optical system implementation suggestions are given here.

A two phase program is proposed. The first phase would establish a single station near the Goddard Space Flight Center to determine the suitability of equipment and design criteria to deep space communication. The second phase would equip up to five selected sites in a world wide network.

DEEP SPACE MISSIONS

Deep space missions may be classified by their ultimate termination point and by the type of measurements made.

In general, deep space missions can be divided into four classes: 1) deep space probes which simply pass through interplanetary space making scientific measurements of the space environment encountered, 2) fly-by missions which have as their objectives a specific planet, but which make scientific measurements of that planet only during the fly-by phase, 3) planetary orbiter missions in which the spacecraft is placed into orbit about the target planet, and 4) planetary entry and lander missions in which the spacecraft or capsule enters the planetary atmosphere and transmits data either directly back to Earth or relays it through the spacecraft bus back to Earth.

The scientific objectives of deep space missions can be considered in terms of the spectrum of measurements to be made and the required position for making these measurements. These may be generally divided into three broad fields: the measurement of gross particles such as micrometeoroids; the measurement of atomic and molecular particles, electrons, protons, etc.; and measurements over the electromagnetic spectrum.

Gross particles (micrometeoroids) can only be measured effectively at the location of the particles since there is no method for making such measurements from Earth. A knowledge of the gross flux of such particles throughout the solar system is important, and the mass/velocity distribution as well as the direction can provide data concerning the history of the solar system.

Low-energy particles must also be measured in situ since there is no known method of measuring their characteristics from Earth. On the other hand, many of the important characteristics of high-energy particles can be measured as well in near-Earth solar orbit as they can in deep space; therefore, such experiments are only valuable in the region where the solar influence terminates and for measuring trapped high-energy particles near a planet. Magnetic field measurements also require local measurements. With respect to neutral particles, measurements should be made outside the region of influence of the Sun and therefore, such a scientific objective can only be carried out on a very deep space probe.

Measurements throughout the electromagnetic spectrum are not valuable to pure deep space missions since these can best be made in the vicinity of the Earth. However, near a planet such as Jupiter or Saturn, high resolution measurements made over the entire spectrum are vital.

CAPABILITY OF COMMUNICATION SYSTEM (LASER OR MICROWAVE) TO MISSION

Missions suited for laser, microwave and for hybrid laser/microwave communication links are noted.

Introduction

It is specifically required by contract NAS 5-9637 that missions be identified which make best use of microwave and laser systems. Specifically the work item reads as follows: "The contractor shall perform overall systems trade-off studies in sufficient detail to identify those missions which will make the best use of Laser/optical microwave, or a combination of microwave and Laser/optical communications and tracking systems."

The analysis required by this portion of the statement of work has been done. It is documented extensively in this final report. The conclusions are documented, although there are some uncertainties.

The decision for the applicability of laser or microwave communication systems depend upon three basic factors. These are: 1) the relative capabilities and expense of the two systems, 2) the mission to be performed and 3) the required data rate. Generally the laser system will show a weight or cost advantage over a microwave system high data rates are required at planetary ranges.

The missions to be performed include those distinguished by being manned or not and those distinguished by their destination (space or heavenly body). Finally, the required data rates are heavily dependent upon the sensors used on the spacecraft, relatively low data rates are required of most sensors with the exception of imagery sensors.

Salient System Features

Before pairing mission and communications systems, some salient features of the two communication systems should be noted. For instance, microwave systems are, to a large degree, implemented e.g., the DSIF. This system is capable of low to medium data rates, 10 to 16,200 bits per second, at planetary ranges, and these data rates can be achieved with relatively simple pointing of the spacecraft antennas.

In the case of laser communications, there is no implementation of a ground station network, and only a limited amount of experimentation is proceeding which could lead to such a network. However, it is possible, within the present state of the art, that laser communication could provide high data rates, 10^5 to 10^8 bits per second, at planetary distances. However, to achieve such performance requires sophisticated transmitter antenna pointing in the spacecraft.

Mission and Type of Communication System

When the general capabilities of laser and microwave systems are compared with the Data Rate Estimates, given in the Table, certain conclusions may be reached, these are noted below.

- A radio communication system should be used for space probes operating at planetary distances. This is largely due to the low data rate which may easily be accommodated by existing radio systems.

- An optical communication system should be used for a planetary orbiting mission. This is due to the very large amount of data which may be gathered using imagery sensors at these long ranges and which will be gathered at high rates for extended periods of time. Thus, not offering an opportunity to store the data and transmitting it at a slower rate.

- An optical communication link is also appropriate for manned lander mission. Here the high data rate obtained from imagery sensors leads to the selection of optical communications.

- In flyby missions the data rate can be high for a short period of time. This allows the use of a storage and playback mode and a radio link. The radio link would also be necessary since, with a flyby mission, continuous communication coverage is usually required during the critical flyby time. This could not be obtained with an optical system unless the additional complexity of an earth orbiting optical receiving station is used to prevent communication interruption by clouds.

- For a manned orbiting mission a radio system is likely best even though high, long term data rates may be expected. The reason for this is the additional difficulty in decoupling man caused mechanical disturbances. These are difficult and expensive (in terms of control system fuel (weight) to decouple from the optical pointing system.

An optical communication system can provide high data rates at planetary distances. Due to the specialized care required in pointing and tracking, this high data rate transmission becomes the principle features oflaser communications. However this is not the only type of communication required by a spacecraft. In fact, there is generally a requirement for continual telemetry data which allows the earth stations to monitor the spacecraft performance and to determine the spacecraft's position. In addition to the transmission of telemetry data, the spacecraft must receive commands and beacon signals from earth. The two functions, commands and telemetry, are accomplished best, by far, with a radio system. Thus it is seen that any optical system is really a combination of laser/optical and microwave, with the microwave being a relatively low performance communication system (and thus much less costly and lighter than a link that transmits the high data gates) and the optical system being designed to transmit the high data rates.

One other laser/microwave hybrid should be noted, although it has been mentioned briefly above. Since it is extremely difficult to guarantee an optically clear path between a space probe and a receiving station on earth, because of clouds, an intermediate receiving site such as a synchronous satellite, may be used to receive and detect the optical signal and then remodulate it on a radio signal for transmission to earth. This type of hybrid system is a very expensive addition to an optical receiving site and therefore would be difficult to justify. However it should be observed that such a relay satellite could be a multiple purpose satellite, being used for other missions such as astronomy investigations.

Data Rate Estimate

	Manned	Unmanned
Space Probe		
Mars range		low
Jupiter Range		low
Flyby		
Mercury		Medium - high
Venus		Medium - high
Mars	Medium - high	Medium - high
Jupiter		Medium - high
Astroids		Medium - high
Orbiter		
Mercury		high
Venus		high
Mars	high	high
Jupiter		high
Lander/Explorer		
Mars	high	high

High data is taken as greater than 10^6 bits/sec. Low data rate is taken as less 100 bits/second. Medium data rate is between these approximate values.

INTRODUCTION

The scope and format of the Reference Data Summary is described.

The Reference Data is material which describes technologies pertinent to laser and microwave space communication. The Reference Data is found in Volume III of this final report and contains parts dealing with the following technologies: Transmitting Power Sources, Optical Modulators, Detectors, Transmitting and Receiving Apertures, Acquisition and Tracking, Prime Power Sources, Heat Radiators, and Background Radiation and Atmospheric Propogation.

Each technology description includes sections dealing with theory. state-of-the-art development, and burden relationships* in addition to introductory sections and, in some cases, a nomenclature section.

The theory is given to introduce the reader to the theory of the technology being discussed. Basic relationships are given but extensive derivations are avoided. The theory is presented as a guide for using the material of the section and as a means to project parameter capabilities.

The documented state of the art lists new variants of the technology and tabulates current parameters and performance.

The burden relationship sections contain the parametric relationships of parameter values as a function of weight and cost. Ancillary equipment required by the technology may also be described.

Nomenclature is intended to apply only to the technology of which it is a part. Thus the same symbol may be used in this final report to represent more than one parameter. However in each instance the symbol is defined and remains the same in that technology description.

The Reference Data Volume, and the great majority of the final report, is written in a format which clearly distinguishes each topic being described. Each topic is largely able to be considered alone, for each contains definitions of terms used references, and tables or figures. The summary of the Reference data which follows is in the same format. In this summary it is intended to present some of the more important concepts of each technology and to introduce the range of material covered.

*Burden relationship are those between a parameter value and weight, cost, or power.

TYPES OF TRANSMITTING SOURCES

Frequency bands are defined for both radio and optical power sources and topics covered are noted.

Radio frequency sources and optical frequency sources are described in terms of operating theory and performance characteristics. The division of the spectrum between rf and optical frequency source types was arbitrarily chosen at approximately 300 microns.

Radio frequency sources include both oscillators and amplifiers, for either may be used as the basic transmitter device. The rf sources are limited to continuous wave devices as cw sources generally are significantly more efficient than non-continuous power sources. A natural classification of rf sources results as a function of frequency because of the fundamental mechanisms involved in the generation of rf energy. The frequency range is divided as follows:

UHF	100 MHz to 1000 MHz
Microwave	1 GHz to 30 GHz
Millimeter	30 GHz to 300 GHz
Submillimeter	300 GHz to 1000 GHz

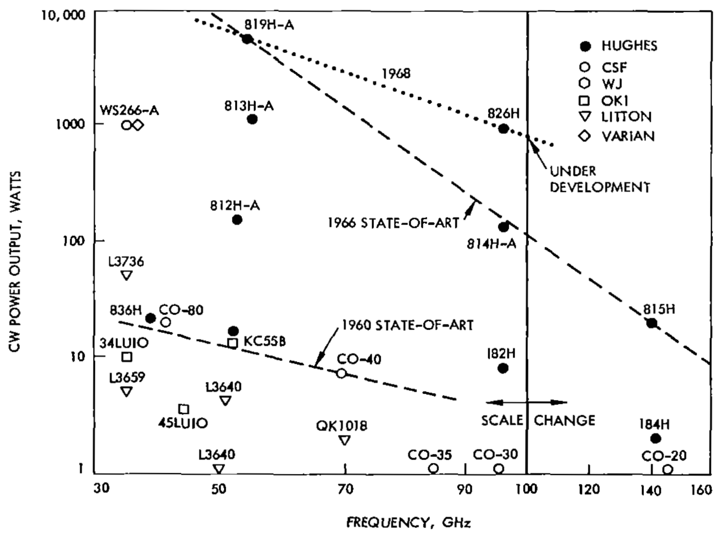
The optical frequency sources include ultraviolet, visible and infrared laser sources (to 300 microns).

The table indicates, in summary form, the sections and subsections which form the Transmitting Source part of the Reference Data.

The figure gives a summary of the power available as a function of frequency for microwave sources. A laser source review is given in the next topic.

Transmitting Power Source Discussion Covers Both Theory and Performance of RF and Optical Frequency Sources

Radio Frequency Sources	Optical Frequency Sources
Theory of Radio Frequency Sources	General Theory of Laser Sources
• *UHF Sources*	*Argon Ion Laser*
• Microwave Sources	CO_2 Laser
Klystrons Traveling-wave tubes Cross-field Devices	Laser Mode-Coupling
	Laser Stabilization
• Millimeter Sources	Laser Oscillators
• Submillimeter Sources	Laser Amplifiers
Performance of Vacuum Tube Sources	Evaluation of Gas Laser Sources
• UHF Sources	
• Microwave Sources	
• Millimeter Sources	
Solid State Microwave Sources	
Weighting Factors	



Power Characteristics of Available High Power CW Sources

Most significant is 35 percent efficiency achieved in the 813H and marked increase in available power which has occurred since 1960. The letter -A stands for amplifier and the letter -O signifies oscillator.

GAS LASERS AS TRANSMITTING SOURCES

A CO_2 transmitter for a spaceborne communication link and an Argon laser for an up-link beacon appear to be the best choice for laser space communication.

The Table summarizes the characteristics of six wavelengths produced by gas lasers. Hundreds of other wavelengths are available, but these six have been selected as representative of each type (ion, molecular, and neutral gas). The reported output power, length and input power are given for the lasers selected.

Notes

1. This is a Hughes airborne quartz laser with a 46 cm bore length ~1 meter overall package length. It requires a magnetic field of ~1000 gauss, which implies a heavy structure and additional power.

2. This laser was reported by Raytheon in Electronic News; it is a quartz tube. The power out is 18 watts, provided the beam in the cavity was chopped to prevent damage to the mirrors.

3. This was produced under carefully controlled conditions at Bell Labs.

4. This is a commercially available Spectra-Physics model 125. 50 mw is guaranteed, but selected tubes produce 100 mw.

5. This is the Spectra-Physics model 125. It may be possible to double the power in a tube this size, but drastic improvements are quite unlikely at this wavelength.

6. This is an Hughes Research Laboratories (HRL) Laboratory-type tube. The output may be doubled, but more power than this is doubtful in a tube this size.

7. This is a TRG Laboratory-type tube and represents approximately two years of effort in developing a high power Xe laser. It is probably close to the ultimate for a tube this size.

8. This is an HRL Laboratory-type tube using flowing CO_2-N_2, mirrors were not optimized; more output power can be expected from this same tube (~20 watts). Seven watts were obtained with the tube sealed.

9. This is the Bell Telephone Laboratories work (C. K. N. Patel, Appl. Phys. Lett., 1 July 1965). A flowing gas system was used with a mixture of CO_2, N_2, O_2, H_2O.

10. This is a BTL result with a tube 4 inches in diameter and 12 feet long. Helium was used. It is difficult to estimate how much power will eventually be obtained from a tube of this size. (C. K. N. Patel).

Gas Laser Performance

Gas	Wavelength, microns	Manu-facturer	Output Power, watts	Length, meters	Input Power, watts	Efficiency	Note
Ar II	0.5	HRL	4.0	0.46	4,000	1×10^{-3}	1
AR II	0.5	RAY	8.0	1.6	20,000	4×10^{-4}	2
He-Ne	0.63	BTL	1.0	5	500	2×10^{-3}	3
He-Ne	0.63	S-P	0.1	1.7	~200	5×10^{-4}	4
He-Ne	1.15	S-P	0.03	1.7	~200	1.5×10^{-4}	5
He-Ne	3.39	HRL	0.01	1.7	80	1.8×10^{-4}	6
He-Xe	3.51	TRG	0.08	2.0	~200	4×10^{-4}	7
CO_2	10.6	HRL	10	2.0	150	6.7×10^{-2}	8
	10.6	BRL	12	2.0	—	3×10^{-2}	9
	10.6	BTL	130	4.0	~1,000	$\sim 1.3 \times 10^{-1}$	10
	10.6	BTL	0.1	0.5	30	3.3×10^{-3}	11

GAS LASERS AS TRANSMITTING SOURCES

11. This is a small, non flow tube, with external mirrors; suitable for spacecraft. This work is due to T. J. Bridges and is rather preliminary. An account of similar tubes appears in the 1 November 1965 Appl. Phys. Letters.

In comparing the various lasers listed in the table, the suitability of the output signal for the communications task at hand must be kept in mind. All of the lasers listed can be made to operate in the lowest order spatial mode (TEM_{00}) alone with more or less difficulty. The task is easier at the shorter wavelengths where the laser output is visible and the characteristic beam size is small (proportional to the square root of the product of wavelength and a cavity parameter related to mirror radius). Mode selection at infrared wavelengths may be done with an image-converter or by using a heterodyne detector. Production of a single-frequency output is still quite difficult because of the longitudinal mode structure of the long Fabry-Perot cavities used. Only the 10.6μ CO_2 and 3.5μ Xenon lines are narrow enough to produce reasonable output by keeping the Fabry-Perot resonator short enough so that only one longitudinal mode oscillates. This is done to the narrow doppler-broadened line widths of these two transitions (~50 MHz for 10.6μ CO_2 and ~120 MH_z for 3.5μ Xe). Even these two transitions will require further mode selection techniques if longer, higher power tubes are considered. Because of the broad doppler line widths of the Ar and He-Ne lasers, single-frequency operation through the use of a sufficiently short Fabry-Perot resonator entails a drastic loss in output power. Techniques involving 3 mirror resonators allow the use of longer tubes at the expense of added complexity both mechanical and electronic (servo-controlled mirror positioning), but still sacrifice output power because the entire line is not used. The most promising technique developed to date is that of intracavity mode locking[1] with a subsequent coherent recombination[2] or selective output coupling[3]. This technique has been demonstrated in the laboratory, but practical power levels at a single frequency are yet to be obtained. In any case the additional complexity will contribute to the weight, length and inefficiency of the laser, although perhaps not to a significant extent.

It appears that, at present, the best laser for optical space communications at present would be a small, efficient, light weight 10.6μ CO_2 laser in the spacecraft with coherent detection (superheterodyne) on the ground, employing a cooled Hg:Ge detector. The up-link would be best handled by a high-power multimode argon laser on the ground, employing pulse amplitude or pulse polarization modulation, and a simple ruggedized photomultiplier video receiver in the spacecraft. These conclusions are, of course, subject to revision as the state of the laser (and detector) art progresses.

---

[1] Harris, S. E., and McDuff, O. P., Appl. Phys. Letts., 5, pp. 205-206, November 15, 1964.

[2] Massey, G. A., Ashman, M. K., and Taig, R., Appl. Phys. Letts., 6, p. 10, 1965.

[3] Hanes, S. E., and McMurtry, B. J., (to be published).

OPTICAL MODULATORS

The interaction of optical and electric or acoustic fields in certain optical materials is the basis for achieving a variety of types of laser beam modulation for useful applications in space communication systems.

Laser modulation is accomplished by passing the beam through an optically transmissive medium in which one or more of the optical transmission parameters is varied by the application of a modulating field. The interaction of the laser beam and the modulating field within the medium makes it possible to achieve a wide variety of types of optical modulation, including intensity, frequency, phase, and polarization.

The advent of lasers has motivated extensive research and development in optical modulation. Laboratory and commercial devices presently are available for obtaining all forms of modulation of visible and infrared lasers. Most of these devices are based on the use of the electro-optic effect or elasto-optic effect in crystals and liquids. Up until two years ago, the best immediately available techniques for modulating infrared lasers (beyond about 1.5 microns) involved the use of elasto-optic, or acoustic effects. However, advances in the technology of growing single-domain ferro-electric crystals, some of which exhibit a strong first-order electro-optic effect, promise a brighter future for modulation up to 5 microns by electro-optic means; and the recent advent of high resistivity gallium arsenide opens the way to practical modulation systems at 10.6 microns.

A detailed assessment of the performance and burdens of existing visible and infrared optical modulators may be somewhat misleading to the designer of future laser systems for space applications because the relevant technology is in a constant state of flux and probably will continue to be so for at least several years. The discovery and perfection of non-linear optical materials and the invention and perfection of modulation interaction structures and devices will lead to continuing improvement in performance and reduction of burdens.

At present, electro-optic modulators for lasers which operate in the wavelength range between about 0.4 and 10.6 microns can provide information bandwidths larger than the maximum believed to be required by space optical communication and tracking systems (i.e., 100 MHz of bandwidth). The burdens of weight and modulator driving power at the longer wavelengths, however, appear excessive. The problems associated with handling very high laser beam powers also have not yet been studied in depth, and may present some additional difficulties. However, advances both in the synthesis of better electro-optic materials, and in the design of modulator structures will provide optical modulators suitable for space communications systems within the next few years.

In the meantime, it would seem advisable to pursue further research in acoustic and other means for modulating infrared lasers above 1.5 microns. Present acoustic materials and techniques have serious limitations in achieving the larger information bandwidths that may be required (i.e., in extending present bandwidths of 1 to 5 MHz, up to 100 MHz).

Other physical processes which may be useful for optical modulation, such as controllable photon absorption in solid-state materials, and magneto-optics, either are not very promising, or are in too early a state of research to evaluate accurately their potential usefulness.

These have been addressed exclusively to the final modulation process of impressing the information on the optical carrier. It should be pointed out that there may be very good reasons for impressing the signal information on a radio-frequency subcarrier, prior to performing the final optical modulation. All of the conventional modulation techniques may be utilized in the preliminary step. This will eliminate the necessity for impressing video or very low-frequency modulation components on the laser beam. The elimination of low-frequency components on the optical signal may provide important advantages both in the ease of design and driving of optical modulators, and in achieving satisfactory transmission through the earth's atmosphere.

Finally, it should be pointed out that research and development remain to be done before the technology will exist to provide optical modulators with fully acceptable performance and burdens for space communication and tracking systems. The programs now in progress, if continued, may accomplish the desired results. This is in an area, however, which needs additional direction and support in order to assure that the results will be forthcoming on a suitable schedule.

OPTICAL MODULATOR CHARACTERISTICS

Advances in the technology of electro-optic modulator materials and design techniques permit a reasonably accurate assessment of expected performance.

It is difficult at this time to make accurate assessment of the performance characteristics of optical modulators which will have continuing value to the designer of laser systems for space communications and tracking. However, great progress has been made in the past few years in the development of optical modulation techniques and materials. This work has demonstrated that all forms of modulation can be impressed on optical carriers in the band between 0. 4 and 10. 6 . At wavelengths longer than 1. 5 , optical modulation technology is in a somewhat more primitive state; but the advent of high grade semi-insulating GaAs as a useful electro-optic modulator material in the infrared region of 2 to 12 has constituted a notable breakthrough for CO_2 laser applications. Moreover, the technology of synthesizing superior grade $LiNbO_3$ and $LiTaO_3$ has made possible useful and efficient modulators in very broadband applications over the wavelength range of 0. 4 to 5 . Research and development of acoustic modulation techniques is progressing at a moderate pace, and acoustic modulators in some instances offer a significant power advantage; but on the other hand they provide modulation bandwidths far short of those believed to be needed in optical space communication systems.

In considering communication and tracking systems using infrared lasers, it must be realized that there is an inherent inverse dependence on modulation efficiency on wavelength at a given driver power level. Thus, for example, a specific modulator element requires 10 times as much voltage at 5 as it does at 0. 5 to achieve the same depth of modulation. In order to keep the power within reasonable limits, it is necessary to (1) extend the interaction length and/or (2) settle for less modulation scheme which can provide a high effective modulation index for intensity modulation and reasonable frequency deviations in optical FM systems with very modest levels of driver power, when the attendant bandwidth limitations are acceptable.

The table presents, in more or less chronological order, a series of electro-optic modulators and their operating characteristics. This listing is by no means complete, but an attempt has been made to itemize those modulators which represent significant advances in their particular regime of applications. Except where otherwise noted, the performance characteristics are applicable for an optical wavelength of 6328Å. The commercial device produced by Isomet Corporation reflects the advanced technology now reached in the field of electro-optic modulator design and production.

Characteristics of Some Electro-Optic Modulators - December 1968

Parameter	TM_{00} Mode Cavity Modulator	Traveling Wave Intensity Modulator	Polarization Modulator (NASA Contract)	Multi-Element Intensity Modulator	Resonant SSBSC Modulator	Traveling Wave SSBSC Modulator	Single Element PCM Modulator	10.6μ Intensity Modulator	Commercial Modulator
Development Status	Built at BTL	Built at Sylvania	Built at Hughes Aircraft Company	Built at Hughes Aircraft Company	Built at Hughes Aircraft Company	Built at Hughes Aircraft Company	Built at BTL	Built at RCA	Product of Isomet Corp.
Material	KDP	KDP	KDP	KDP	KDP	KDP	$LiTaO_3$	GaAs	y-cut ADP
Crystal Dimensions	1 cm long x 2.5mm dia.	100 cm long x 2 mm wide	50 x 0.4 x 0.4 cm	16 each 1/4" x 1/4" x 1/2"	2 each 1 1/2" long x 1/2" dia.	80 x 0.4 x 0.4 cm	1 x 0.025 x 0.025 cm	6, 7 x 0.3 x 0.3 cm	20 x 0.4 x 0.4 cm
Optical Attenuation	0.1 dB	6 dB	1.5 dB	0.3 dB	1.0 dB	2.0 dB	1.5 dB	0.4 dB	0.4 dB
Useful Optical Range	0.4 - 1.5μ	0.4 - 1.5μ	0.4 - 1.5μ	0.4 - 1.5μ	0.4 - 1.5μ	0.4 - 1.5μ	0.4 to 5μ	2 to 12μ	0.25 to 0.75μ
Modulation Frequency	3 Gc	Baseband	Baseband	Baseband	850 Mc	200 Mc	Baseband	Baseband	Baseband
3 dB Bandwidth	4 MHz	3 GHz	30 MHz*	10 MHz*	5 MHz	100 MHz	220 MHz*	100 MHz*	>100 MHz
Modulating Power	1.5 W	12 W	20 W	12 W	3 W	10 W	250 mW	70 W	50 W
Modulation Index	0.13	~1.0	0.5	0.5	0.01	0.3	0.4	0.1	0.5
Extinction Ratio	Unknown	Unknown	8:1	250:1	NA	NA	80:1	~80:1	70:1
Weight	Unknown	Unknown	20 lbs	2 lbs	15 lbs	25 lbs	Unknown	Unknown	Unknown
Size	Unknown	~100 in^3	144 in^3	30 in^3	850 in^3	216 in^3	Unknown	12 in^3	80 in^3

*3 dB Bandwidth limited by modulator driver and not by the electro-optic structure.

HETERODYNE DETECTION

Heterodyne performance for radio and optical frequencies is given. Optical heterodyne detection will probably find its greatest application in a wide band data link from a space probe.

The performance of optical heterodyne detectors is similar to that of radio heterodyne systems but still differs markedly due to the high operating frequency. This has the effect of changing the dominant noise contribution from a spectral density given by kT (k is Boltzmann's constant and T absolute temperature) to a spectral density given by $h\nu$ where h is Plank's constant and ν is the operating frequency. In general, the noise power spectral density N increases with frequency.

Ideally,

$$N = \frac{h\nu}{e^{h\nu/kT} - 1} + h\nu$$

This curve is plotted as a function of frequency in the figure, for various noise temperatures, T in °K. The figure compares detector performance over the radio-to-optical spectrum and shows the projected capability of optical detectors (using the above equation) in comparison with known radio receiver performance.

More recently heterodyne detectors have been constructed at both 3.39 microns[1] and 10.6 microns[2]. The performance of these detectors is much improved over that of the direct detector. (Direct detection is discussed in the next topic.)

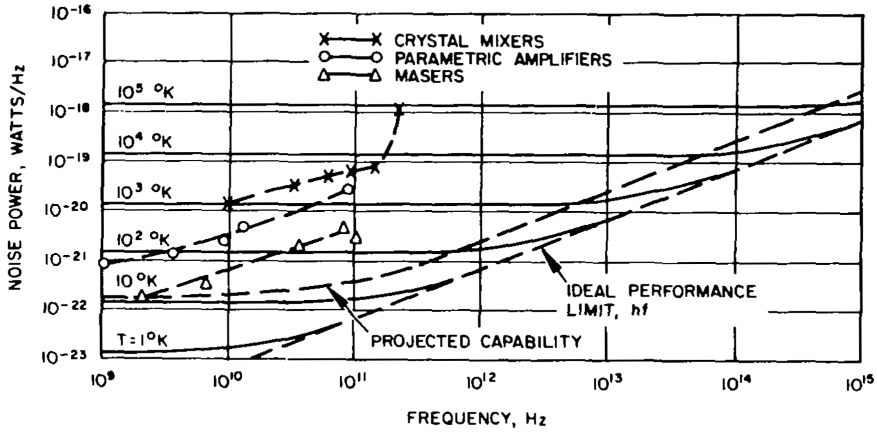
The radio frequency detectors indicated in the figure are of two types, a heterodyne mixer and a heterodyne mixer preceded by a low noise amplifier. When the gain of the amplifier is high its low noise characteristics become the dominant noise contribution of the detecting system. Five types of low noise amplifier may be considered for a space communication link. These are discussed briefly below.

Transistor Amplifiers

Microwave transistor amplifiers are relatively new devices which have promise of moderately low noise figures. At the present time noise temperatures of 200 to 265 °K can be obtained at frequencies up to about

[1] Goodwin, F. E., "A 3.39 micron Infrared Optical Heterodyne Communication System," IEEE Journal of Quantum Electronics, QE-3, No. 11, pp. 524-531, November 1967.

[2] Goodwin, F. E. and Nussmeier, T. A., "Optical Heterodyne Communications Experiments at 10.6μ," Presented at International Quantum Electronics Conference, Miami, Florida, May 14-17, 1968.



Heterodyne Receiver Noise Performance

HETERODYNE DETECTION

1 GHz with approximately 20 db gain. It is estimated that in ten years 120° to 170°K noise temperatures are likely at 2 GHz and feasible up to 15 GHz. Transistor amplifiers appear to have their most useful application as a second stage amplifier following an ultra low noise amplifier.

Tunnel Diode Amplifiers

The tunnel diode amplifier (TDA) is the simplest solid-state microwave amplifier and has moderate gain and noise characteristics. Noise temperatures range from about 360°K at 1 GHz to 520°K at 10 GHz using gallium antimonide diodes. Germanium diodes have about 1 db higher noise figures but are available for operation up to about 20 GHz. Single stage amplifiers normally provide about 17 db gain. However, stable gains as high as 30 db can be obtained by careful attention to temperature control and power supply stability.

Traveling Wave Tubes

These devices offer high gain and moderately low noise figures. Noise temperatures in the 360 to 440°K range are presently obtainable over narrow bandwidths up to 2 GHz. It is unlikely that noise temperatures below about 225°K will be consistently obtained in the next decade. The two major noise sources in a TWT are beam shot noise and thermal noise from the attenuator.

Parametric Amplifiers

Parametric amplifiers have demonstrated room temperature noise performance superior to that of transistor and tunnel diode amplifiers and cryogenic noise performance approaching that of the maser. In recent years the uncooled parametric amplifier has achieved a level of reliability that has permitted applications on a broad basis and in large numbers. Noise temperatures range from about 60°K at 1 GHz to 250°K at 10 GHz for well-designed narrow band amplifiers.[3] When cooled to 20°K, noise temperatures between 14°K at 1 GHz and 30°K at 10 GHz are possible with careful design using presently available components.

Masers

Masers find applications in special areas where the ultimate in low noise performance is either dictated by technical requirements or provides the most economical solution to the problem. The noise temperature of the maser itself is approximately that of its physical temperature, about 50°K. To this must be added the noise contribution of the section of input transmission line over which the temperature transition to room temperature is made. For frequencies in the range 1 to 20 GHz this contribution can be held to 5 to 10°K giving an overall maser noise temperature of 10 to 15°K. Gains of better than 30 db with bandwidths of 1 to 2 MHz or more are readily obtainable with a cavity maser. The major disadvantage of

[3] Matthei, W. G. "Recent Developments in Solid-State Microwave Devices," The Microwave Journal, 9, No. 3, pp. 39-47, March 1966.

masers is that they must operate at a temperature of a few degrees Kelvin in order to provide sufficient gain. The complexity and cost of a cryogenic system increases rapidly as the temperature approaches 0°K.

Future improvements in the maser are likely to be in the area of reliability and cost reduction.

The signal-to-noise ratio for a radio or optical heterodyne system is them:

$$S/N = \frac{P_T \, G_T \, G_R \, L}{NB} \left(\frac{\lambda}{4\pi R}\right)^2$$

where

P_T = the power transmitted

G_T = gain of the transmitting antenna

G_R = gain of the receiving antenna

B = noise bandwidth

λ = wavelength

L = miscellaneous losses in the system due to hardware, atmosphere, mispointing, etc.

R = range

DIRECT OPTICAL DETECTION

Direct detection is practical only for optical frequencies. It will probably find its greatest application as a beacon link to a deep space vehicle.

In direct detection, the output signal is dependent only upon the input signal and background power. (No local oscillator power).

Visible frequency detectors are largely of the direct detection type. These operate quite efficiently due to the relatively large photon energies at these frequencies.

The equation describing the signal-to-noise ratio for direct detection is:

$$\frac{S}{N} = \frac{\left[\frac{G\eta q}{hf} P_C\right]^2 R_L}{kTB_o + G^2\left(\frac{\eta q}{hf} P_C + \frac{\eta q}{hf} P_B + I_D\right) R_L \, 2qB_o}$$

where:

G = detector gain

η = detector quantum efficiency

q = electronic change, 1.602×10^{-19} coulombs/electron

h = Plank's constant 6.624×10^{-34} watt sec. sec

f = light frequency, Hz

P_c = received carrier power, watts (defined in previous topic)

R_L = load resistance, ohms

k = Boltzmann's constant, 1.38×10^{-23} watts/Hz °K

T = Amplifier noise temperature, °K

B_o = Amplifier bandwidth, Hz

P_B = Background received power, watts

I_D = dark current, amps

Symbolically this is

$$\frac{S}{N} = \frac{\text{Signal Power}}{\text{Thermal noise power} + \text{shot noise power} + \text{background noise power} + \text{dark current noise power}}$$

In any detector application it is necessary to evaluate this equation and adjust the parameters such that an adequate signal to noise ratio is obtained.

The background power, P_B, can be calculated from the characteristics of the background source and from the communication parameters. The background characteristic is the spectral radiance in watts/cm^2-micron-steradian. The communication system parameters of concern are the receiving area, cm^2; the passband, microns; and the solid angle of the source as viewed by the receiver, steradians*. The product of these communication system parameters with the spectral radiance gives the background power. Consider the following example. The background irradiance is 5×10^{-4} watts/cm^2-micron-steradian (see page 43), the area of the receiver is 75 cm^2, a 2 micron optical filter is used and the field of view is 0.01 micro steradian. The received power, P_B, is then

$$P_B = (5 \times 10^{-4})\,(75)\,(2)\,(10^{-8}) = 7.5 \times 10^{-10} \text{ watts}$$

It is sometimes convenient to express the signal power and the noise power in terms of the signal photons per bit, $\mu_{S,B}$, and the noise photons per bit, $\mu_{N,B}$, as

$$\mu_{S,B} = \frac{P_C}{hf\,R_B}$$

$$\mu_{N,B} = \frac{P_B}{hf\,R_B}$$

where R_B is the bit rate in bits per second.

*The smallest solid angle is used of the receiver field-of-view and the source extent. For a point source the energy is expressed as watts/cm^2-micron.

RF TRANSMITTING AND RECEIVING APERTURES

Phased array and parabolic dish antennas are compared.

High gain antennas may be designed as arrays of low or moderate gain elements, or as large area reflector surfaces illuminated by moderate gain feed elements. Array elements, for the operating frequencies of interest for space communication, are in general heavier than a reflector antenna of the same gain. This is attributable to need for relatively complex radiating element structures as contrasted to a simple reflector surface, and to the requirement for a complex feed system for the array antenna as contrasted to free space for the reflector antenna. Conversely array antennas have an inherent capability for forming multiple beams which may be switched rapidly from one beam to another with no moving parts. These characteristics overpower weight considerations for specialized communications missions and lend to their selection. The reflector antenna is suitable for specific area coverage broadcast satellites and for wide bandwidth data links for planetary and deep space probes.

Two types of directive antennas are most commonly used for space communications. These are the parabolic dish and the plannar array antenna.

Reflector-Type Antenna. This antenna has two basic components: a relatively large reflecting surface (most often paraboloidal) and a feed structure. When maximum antenna gain is required, as for space communication and tracking, the reflector size is chosen to be as large as practical and the feed is normally designed to illuminate the reflector with an intensity at the reflector edges that is approximately 10 db below that at the center.

The efficiencies of reflector-type antennas with a front-mounted feed are typically 55 percent, with 65 percent being the upper realizable bound. The efficiencies of cassegrainian type antennas are typically 60 percent with 70 percent being the upper realizable bound.

The figure illustrates the performance of several large ground based antennas as a function of wavelength, as documented by Ruze.[1]

In addition to earth antennas, parabolic antennas have been used on the Pioneer spacecraft and the Mariner spacecraft.

Phased Array Antenna. This type of antenna consists of an array of radiating elements with either fixed or variable relative phase differences. Those with fixed relative phase differences are referred to as planar

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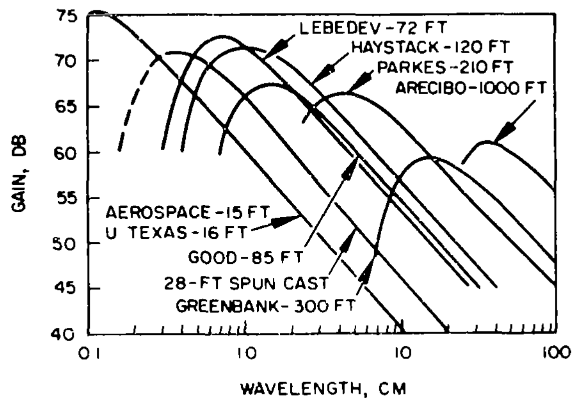
[1] Ruze, J. "Antenna Tolerance Theory - A Review," Proc. IEEE, pp. 633-640, April 1966.

arrays and require mechanical pointing. Those with variable relative phase differences require external electronic controls to properly phase the elements to form a beam in a desired direction. When maximum antenna gain is required, as for space communication and tracking, all the elements of the array are excited equally and the relative phase between elements is adjusted for a beam normal to the plane of the array.

The weight, complexity, and cost of the variable phase shifters needed for those antennas with variable phase differences have deterred space applications of electronically scanned phased arrays. Planar arrays have been used on the ground and even in space when the type of space vehicle stabilization permitted mechanical beam steering.

A planner array antenna was used on the Surveyor spacecraft. This antenna measured 38 x 38 x 2 inches and had a gain of 27 db at 2300 MHz. Plannar arrays have advantages of higher efficiency and lower volume than parabolic antennas of equivalent gain. Their chief disadvantage is higher cost.



Gain of Large Paraboloids

OPTICAL FREQUENCY APERTURES

Optical beamwidths appropriate for space communication range from 1 to 1000 microradians.

The optics used in a laser communications system are a major design consideration. To obtain improved communication system performance using optical wavelengths requires each area of the technology to be examined such that potential implementation choices, basic limitations and interface requirements be understood.

The optical transmission aperture must provide a beam which is as narrow as possible to concentrate the transmitted energy at the receiver. This beamwidth produces one of the most difficult problems for optical communications and is therefore examined briefly below.

The beam spread of a perfect, unobstructed optical system can be depicted by a plot of the Airy Disk shape where the abscissa would be intensity of the energy and the ordinate would be the angular spread. The angular spread as measured by the diameter of the first ring of zero energy would be given by

$$\theta = \frac{2.44\lambda}{D} \quad (1)$$

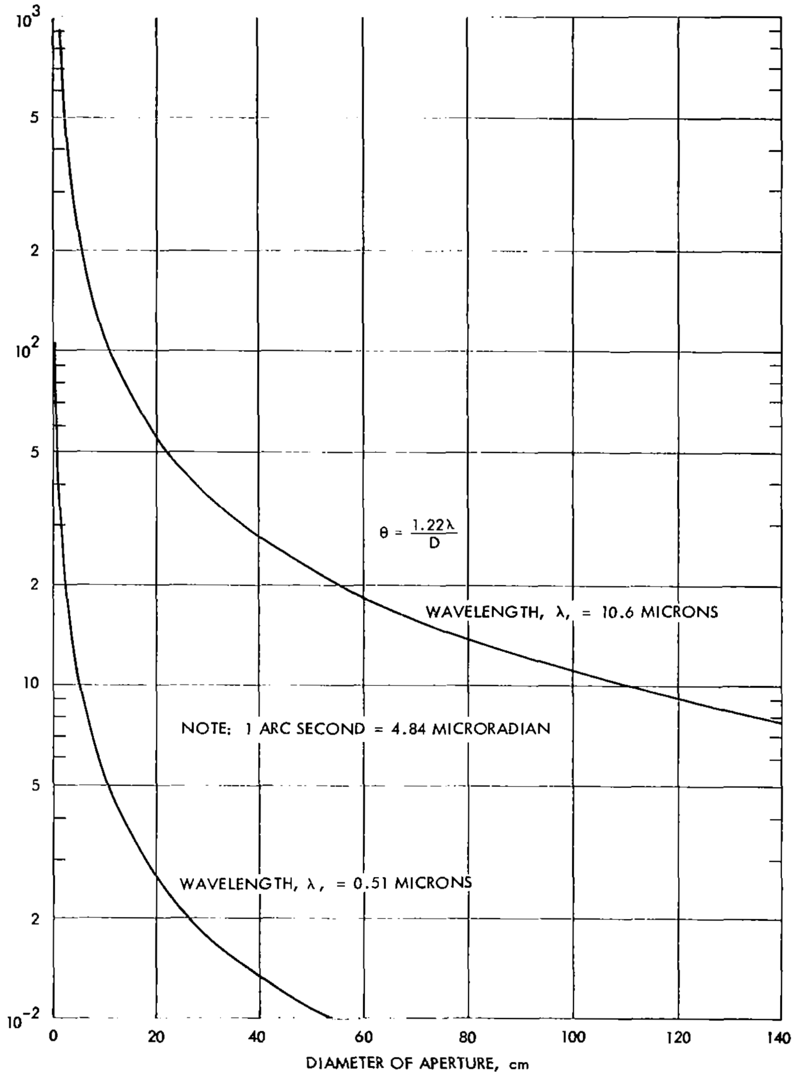
where

θ is the angular spread, radians

λ is the wave length

D is the aperture diameter

In practice however, the angular diameter that is useable is necessarily less than this and is taken at the half power points to be $\theta = 1.04\lambda/D$. (Another measure sometimes used for measuring beamwidths is the resolution of the aperture. Two adjacent point sources are considered to be resolvable when separated by $\theta = 1.22\lambda/D$.) The fact that the beam spread is inversely proportional to the aperture favors the use of a large diameter transmission unit. The narrow beamwidths of diffraction limited optics place severe pointing prbblems on the pointing and tracking system. As a measure of the pointing accuracy required, the diffraction limited beamwidth is plotted in the figure as a function of aperture for wavelengths of 0.51 and 10.6 microns. These results are possible only for excellent seeing when using the larger diameters. Such seeing may well be found only outside the Earth's atmosphere. As is seen from the figure, beamwidths as small as 1 microradian may be considered for visible light, beamwidths in the order of tens of microns are more appropriate for 10.6 micron transmission.



Diffraction Limited Beamwidths at Optical Frequencies

ACQUISITION AND TRACKING

Acquisition and tracking includes subtopics of system requirements, performance analysis, tracker functions, tracking performance measured on a probability basis, and component burden relationships.

The advantage promised by laser communication is gained through the use of very narrow optical transmitter beamwidths allowing transmitter power requirements to be correspondingly small. This, in turn, requires very accurate pointing of the laser transmitter.

The optimum acquisition and tracking system for a particular communication task depends on a host of mission parameters. For instance the transmission of data from a deep space vehicle (DSV) to an earth base receiver requires the spacecraft orientation with respect to a reference coordinate system to be determined. Then the spacecraft must be oriented so as to acquire a cooperative laser beacon at the receiver site. The ground beacon must be pointed to illumine the spacecraft taking proper account of atmospheric irregularities. An optional intermediate step is to have the ground based optical tracker acquire the spacecraft (by means of a broad beam on-board beacon) refining the knowledge of its position so that the ground beacon beamwidth may be narrowed. After the DSV transmitter has been pointed so that it irradiates the earth receiver, the tracking system must continue to point with sufficient accuracy that contact is maintained. The tracking system may be open or closed loop, depending on whether error information required to keep the transmitter beam properly oriented is generated at the receiver or at the transmitter. In either case, the acquisition and tracking system must take into account such factors as:

Relative motion between the tracker and the target.

Coordinate reference errors.

Signal propagation delays.

Aberration effects due to relative acceleration of the transmitter and receiver.

Perturbations of the spacecraft.

Atmospheric effects.

The solution to the acquisition and tracking problem begins by considering the requirements imposed on the system by the peculiarities of the mission and by the receiver location. Next, the acquisition and tracking system performance may be analyzed in terms of these constraints and the system parameters which contribute to the overall pointing error. Then the various functions performed by the general (typical) optical tracker may be delineated and a mathematical description of the performance of these functions in the presence of noise presented. In particular, system performance measures such as probability of detection, probability of acquisition, probability of false alarm, loss rate, tracking accuracy, etc., can be established in terms of the system parameters such as beacon beamwidth, power, receiver FOV, background noise, dark current noise, etc.

Conventional forms of tracking implementation such as a pulsed beacon (monopulse) system utilizing a quadrant photomultiplier and a CW beacon using pulsed position modulation (PPM), amplitude modulation (AM) and frequency modulation (FM) may be used.

The state of the art and burden of components which significantly affect acquisition and tracking system performance, such as star sensors, sun sensors and attitude control and stabilization devices, is surveyed.

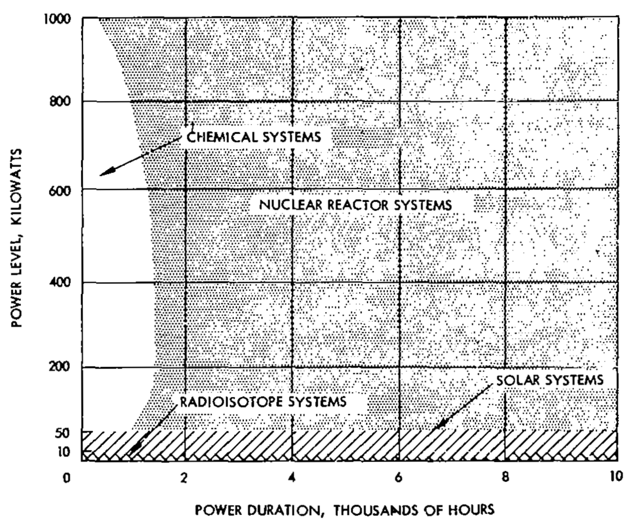
PRIME POWER SYSTEMS

The type of power source used depends upon the mission, its duration and the power requirements.

The selection of a spacecraft power system for a specific mission depends on the power requirements of the mission, the mission duration, and the environment in which the system must operate.

Spacecraft power systems may be classified into three general categories according to the initial energy source as solar, nuclear, or chemical, The weight of solar and nuclear systems is generally not a strong function of mission duration, whereas the weight of the chemical system is decidedly so. Typical power system selections based on a solar distance of 1 AU* are shown in the figure[1] as a function of power level and mission duration. Nearly every power system will include some provision for energy storage to provide for peak power demands and, in the case of solar systems, to provide continued power during periods of solar eclipse. The extent and type of energy storage required depends critically on the exact mission power history and, in the case of solar systems, on the solar illumination history.

The table is a summary of the weight needed to provide an output power at a variety of ranges (Planets) for different types of power sources.



Power System Range of Application at Near-Earth (1 AU) Solar Distance

*1 AU (astronomical unit) 149.6 x 10^6 km.

[1] 1967 NASA Authorization, Part 4, United States Government Printing Office, Washington, D.C., 1966.

Power System Weight, Kilograms

Probe Near:	Mercury				Venus				Earth				Mars			Jupiter		
Distance from Sun, km	57.7×10^6				108×10^6				149×10^6				227×10^6			775×10^6		
Expected Communication Distance from Earth, km	115 to 190×10^6 (1968)				40 to 190×10^6 (1970)				10^4				90 to 310×10^6 (1973)			600 to 890×10^6 (1973)		
Mission Duration, days	82 to 152				72 to 210				30				118 to 260			450 to 1200+		
Power System Type / Output Power, watts	Solar Photovoltaic	Solar Thermionic	Reactor Thermoelectric	Radioisotope Thermoelectric	Solar Photovoltaic	Solar Thermionic	Reactor Thermoelectric	Radioisotope Thermoelectric	Solar Photovoltaic	Fuel Cell	Reactor Thermoelectric	Radioisotope Thermoelectric	Solar Photovoltaic	Reactor Thermoelectric	Radioisotope Thermoelectric	Solar Photovoltaic	Reactor Thermoelectric	Radioisotope Thermoelectric
	Total Power System Weight, kilograms																	
10	0.181	0.363		2.27	0.177	0.272		2.25	0.227	4.44		2.25	0.5		2.25	5.8		2.25
25	0.454	0.953		5.67	0.434	0.643		5.67	0.56.7	11.1		5.67	1.22		5.67	14.4		5.67
50	0.909	1.86		11.3	0.84	1.28		11.3	1.13	22.2		11.3	2.4		11.3	28.9		11.3
100	1.81	3.72		22.7	1.77	2.56		22.7	2.27	44.4		22.7	4.81		22.7	57.8		22.7
250	4.54	9.30		56.7	4.43	6.43		56.7	5.67	111		56.7	12.0		56.7	144		56.7
500	9.09	186.0	311	117.0	8.4	12.8	310	117.0	11.7	222	310	117.0	24.0	310	117.0	289	310	117.0
1000	18.1	37.2	375	227	17.7	25.6	376	227	22.7	444	376	227	48.1	375	227	577	375	227
2000	36.3	74.4	488		35.4	51.3	488		45.4	890	487		96.2	488		1155	488	
5000	90.9	186	1080		84	127	1075		113.2	2220	1080		240	1085		2880	1085	
7500	136.0	279	1625		133	193	1625		170	3330	1625		356	1625		4330	1625	
10000	181.0	372	1665		177	256	1665		227	4440	1665		481	1665		5790	1665	

Notes: 1) Assumes no batteries.
2) Power conditioning losses and weights not included.

HEAT EJECTION SYSTEMS

An active heat exchanger is one in which the heat is conveyed from the heat source to the radiating element by a moving coolant or moving mechanical parts, while a passive heat exchanger has no moving parts.

Heat ejection systems may be classified as active or passive (see the figure). In the most general sense, an active system is one which embodies moving parts (e.g., a coolant fluid or a thermal switch) while a passive system does not. In typical active systems heat is conveyed to the radiating surface by first transferring it to a fluid medium which is then physically transported to the radiator where its heat is ejected. In a passive system heat is conveyed to a radiating surface and dissipated from it by purely static processes.

Passive Heat Ejection

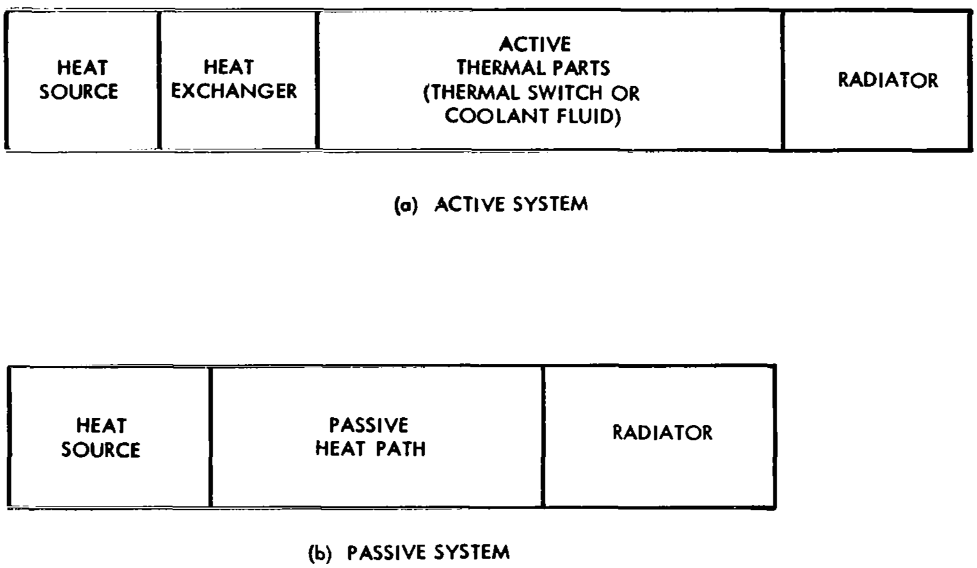
Passive heat ejection systems are preferable when they can meet the requirements because of their extreme simplicity and concomitant lighter weight, lower cost, and higher reliability. They consist merely of a conducting path between the heat source and an external radiating surface, often a part of the spacecraft structure, having a highly emissive surface coating with low absorptivity. The limitation on their utility is almost always excessive temperature gradients in the conducting path as a result of thermal resistance.

Passive and active heat ejection systems differ in the method of conducting the heat from one point to another but the same considerations apply to the actual radiators of heat.

Active Heat Ejection

Active heat ejection systems generally consist of a heat exchanger to transfer heat from the transmitting source to the cooling fluid, the necessary plumbing to convey the fluid to the radiator, and the radiator itself. Of these, the radiator proper is the major contributor to the thermal control system cost, weight, and area. The heat exchanger at the transmitting source is an integral part of the source and is characteristic of it. The remaining system components – plumbing, pumps, controls and the coolant – are of less significance than the radiator with respect to cost, weight, and volume. They are, in any event, peculiar to a specific vehicle and communication system configuration.

Both condensing and non-condensing active heat ejection systems are useful. Condensing (two phase) systems are most applicable to dynamic power systems. Non-condensing (single phase) systems appear more applicable to cooling transmitting sources since boiling of the coolant fluid in condensing systems introduces vapor pockets and leads to local hot spots in critial areas. A very attractive active heat ejection system for spacecraft is the heat pump.



Heat Ejection System Constituant Parts

BACKGROUND RADIATION

Background radiation can seriously degrade to radio and optical space communications. Typical Radio and Optical values of background are given.

The effect of external noise is of great significance in determining ultimate communication system performance. The principal types of noise encountered are:

1. Cosmic noise, originating outside the solar system
2. Terrestrial noise, originating from the earth or its surrounding atmosphere
3. Solar system noise, other than terrestrial, originating from the sun, the planets, or their satellites.

Radio Background Radiation. The variations of noise contributions to the receiver (antenna) effective noise temperature are plotted in a composite form in Figure A.[1] As is seen there is a minimum temperature range in the approximate band of 1.5 to 8 GHz. The relatively low noise contribution from sources external to the receiver in this band makes it desirable for high performance deep space to earth communication links. A refined study of this type has led to the selection of the 2290 to 2300 MHz band for the DSIF receiving frequency.

Optical Background Radiation

Although there are several background conditions that would interfere with optical communications, a night sky may be taken as a nominal situation.

S. K. Mitra[2] estimates the contribution of various sources of night sky radiance as follows:

Starlight	30%
Zodiacal light	15%
Galactic ight	5%
Airglow	40%
Scattered light from last 3 sources	10%

These estimates are for visible wavelengths and for conditions several hours after sunset with no moon. All these components of night emission vary with direction, time, atmospheric and meteorological conditions. Values of night sky radiance presented here are typical.

[1] Grimm, H. H. "Fundamental Limitations of External Noise," IRE Trans. Instrumentation pp 97-103, December, 1959.

[2] Mitra, S.K., "The Upper Atmosphere," Asiatic Society, Calcutta, India, 1962.

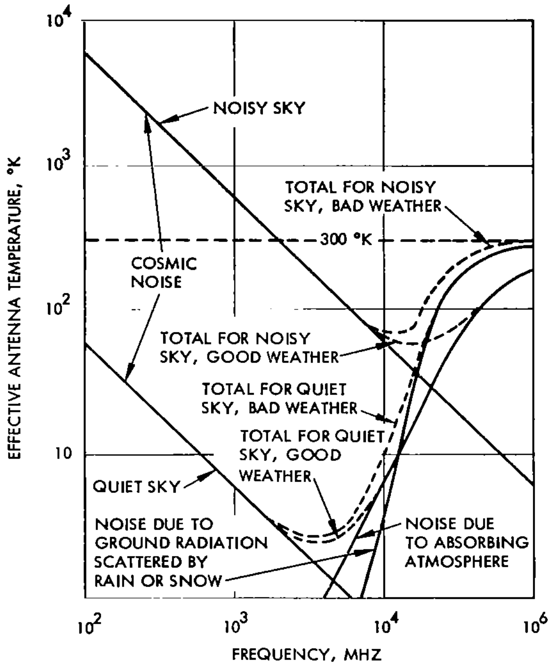


Figure A. Optimum Antenna Noise Curves

BACKGROUND RADIATION

According to Mitra, peak sky radiance due to stellar sources is of the order of 10^{-1} watts/cm^2-steradian-μ at 0.55μ and follows approximately a Planckian spectral distribution. The effective irradiance produced at ground level is 3.34 x 10^{-10} watts/cm^2 at 0.55μ. These figures are 1/4 to 1/6 the actual visible light observed from the night sky at a dark location on a clear night. The remaining contributions come from diffuse sources. The principal noise interference problem due to stars is the result of the relatively small number of very bright stars.

Except for the narrow intense N_a and H atomic lines, relatively light sky emissions appear between 0.1 and 1.0 microns. Beginning at 1.0 microns intense OH molecular bands appear as "air glow." Above 2 microns thermal emission from the dense lower atmosphere obscures the air glow.

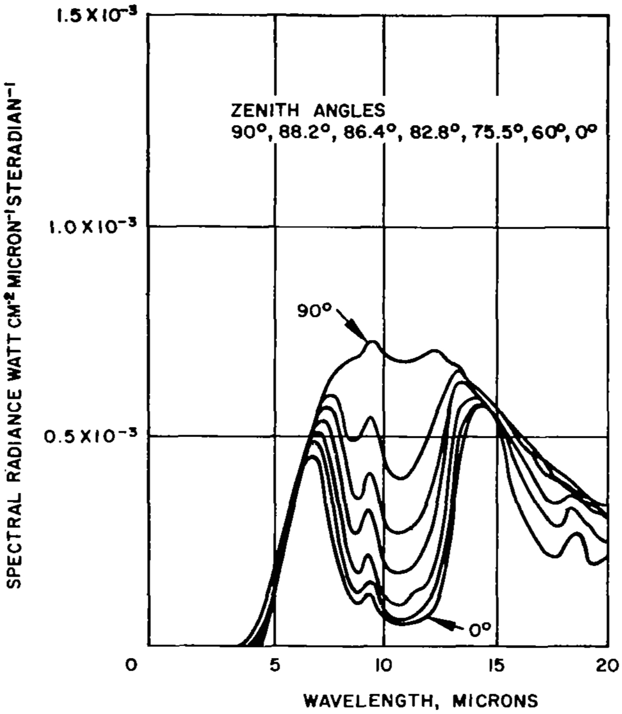


Figure B. Spectral Radiance in the Infrared of a Clear Sky for Several Elevation Angles Above the Horizon

These spectra were measured at an elevation of 11,750 feet, at night, with an ambient temperature of 8°C.

ATMOSPHERIC ATTENUATION

Atmosphere attenuation in the atmosphere is due to water, water vapor, oxygen and other absorbing gases. Plots are given showing values of microwave and optical attenuation.

Radio Frequency Attenuation

Absorption in the ionosphere is very small for microwave frequencies. The effect of ionospheric attenuation can be approximated by assuming that each 0.1 db of attenuation is equivalent to 7°K antenna noise temperature. Ionospheric absorption is also negligible for frequencies greater than 0.3 GHz.

Tropospheric absorption is due almost entirely to water vapor and oxygen. A summary propagation data for a horizontal path, including rain and fog is given in Figure A.

Optical Frequency Attenuation

There are several transmission windows in the infrared as indicated in Figures B and C but roughly half of the spectrum is still blocked by molecular absorption bands. The density of absorption bands decreases in the near infrared and visible regions as shown in Figure B[1]. The curves, given for several values of zenith angle, are for very clear atmospheric conditions.

It is important to note that the atmospheric absorption bands comprise a large number of sharp absorption lines not resolved on the scale of the curves shown. For the eseentially monochromatic radiation generated by lasers, windows may exist within these bands or conversely, relatively isolated absorption lines may exist in apparent windows. Thus high-resolution spectral measurements are necessary in the vicinity of laser lines of interest.

High-resolution solar spectra, which have been taken for many years, represent the best source of information on atmospheric absorption lines. While these measurements have generally been made at high altitudes in order to minimize atmospheric effects and do not provide absolute data on transmission through a standard atmosphere, the measured lines at which attenuation occurs are still strong and serve to identify those wavelengths which must be avoided in the design of a ground-based laser communication link. A detailed study of the absorption spectrum in the vicinity of a number of laser lines has been made.

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[1] Chapman, R.M., and Carpenter, R., "Effect of Night Sky Backgrounds on Optical Measurements," Tech. Rpt. 61-23-A, Geophysics Corp. of America, May 1961.

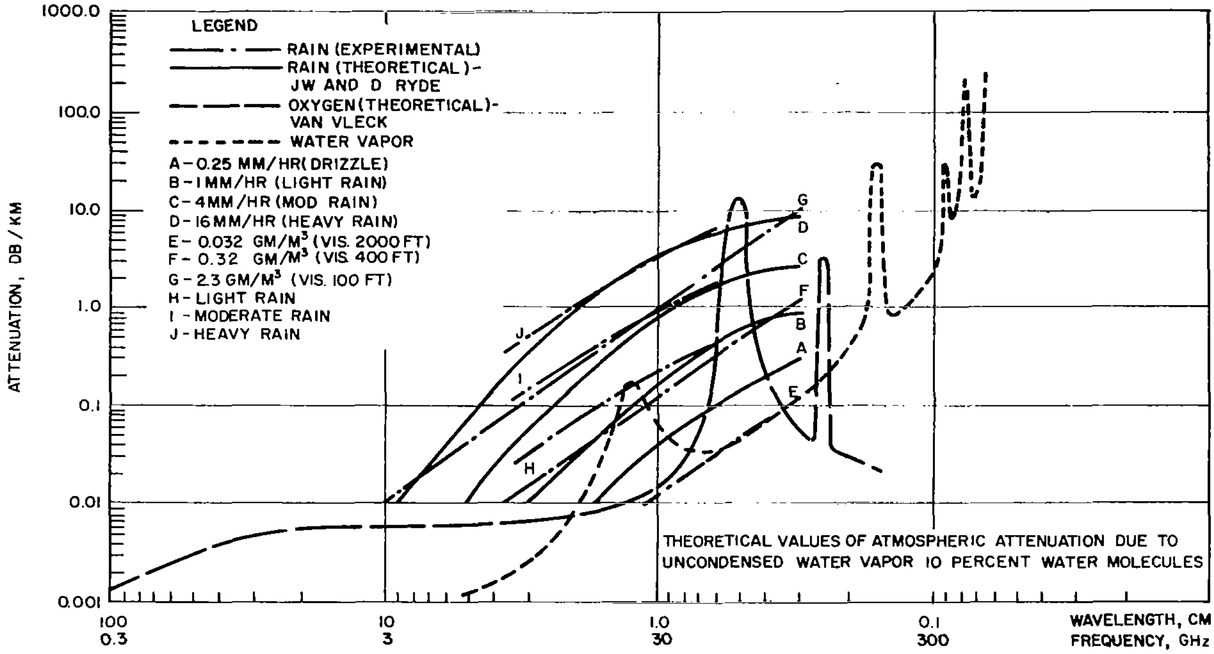

Figure A. Atmospheric Attenuation Summary

ATMOSPHERIC ATTENUATION

Provided the laser wavelength does not coincide with an absorption line, attenuation in the atmosphere will be due to scattering effects. The attenuation at short wavelengths is due to molecular (Rayleigh) scattering of the radiation for which the scattering coefficient varies as $1/\lambda^4$. This together with absorption by ozone in the upper atmosphere accounts for the sharp cutoff of transmission in the ultraviolet as shown in Figure B. Scattering from aerosol particles and droplets in the first few kilometers of the lower atmosphere also plays a major part in attenuation of electromagnetic radiation in the visible and near-infrared regions. For this type of (Mie) scattering (where particle dimensions are comparable with wavelength) the wavelength dependence of the scattering coefficient is a function of particle size and type, but for typical aerosol distributions encountered, experimental measurements suggest that the dependence is about $1/\lambda$.

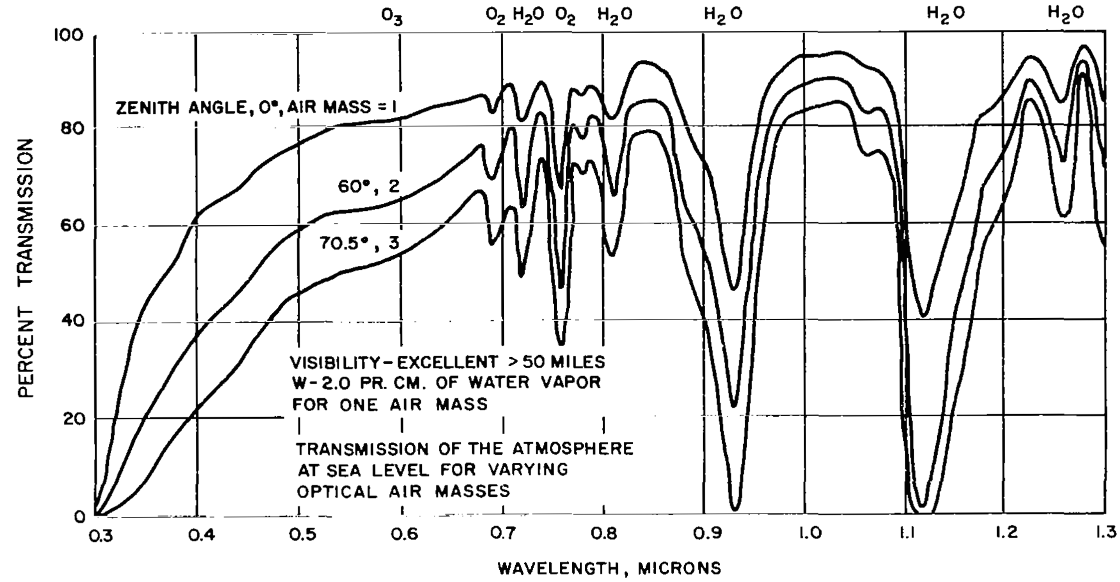

Figure B. Atmospheric Transmission, 0.3 to 1.3 Microns

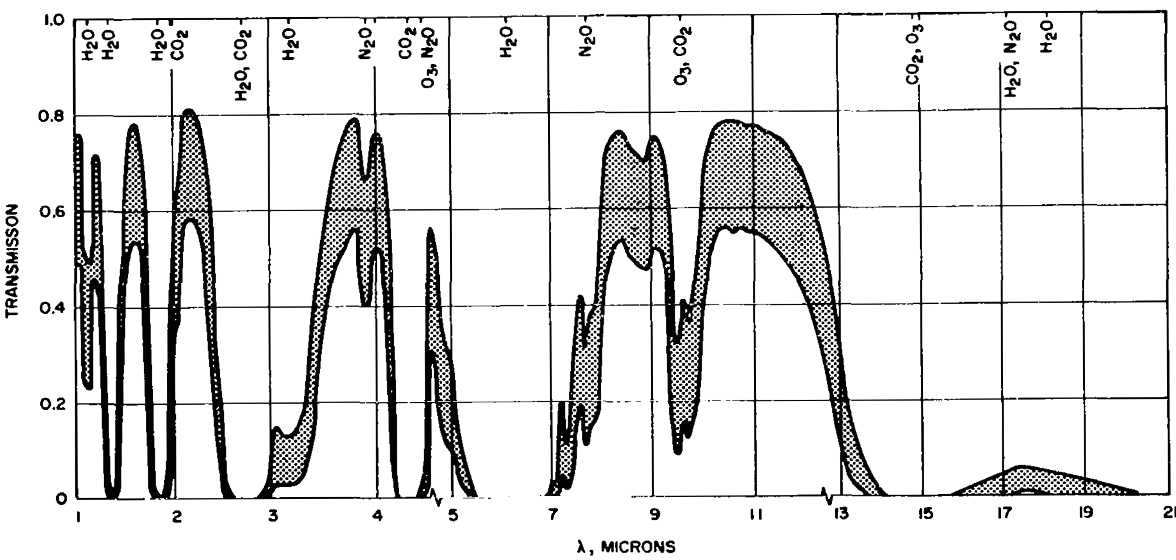

Figure C. Transmission of the Atmosphere in the Infrared at Sea Level for Zenith Angles from 20 to 70 Degrees

Absorbing factors: CO_2, N_2O, CH_4, CO, O_3, and haze (visibility = 32 km).

THE PURPOSE FOR A COMMUNICATIONS DESIGN CRITERIA (METHODOLOGY)

A comprehensive communications design criteria (methodology) has been developed to provide impartial evaluation of communication systems.

Scientific objectives and communications requirements for deep space missions must be related to communications systems in a logical and impartial manner in order to evaluate fairly the several communication system choices available. In particular, it is desirable to evaluate both laser and radio communications systems impartially, otherwise system designs may be formulated which lead to unfair comparisons.

A design criteria has been developed during this contract. It is based upon two measures, that of determining the lightest weight system to provide a given performance and that of providing the least expensive system to provide a given performance. This has been called a "Communications Methodology". It has been programmed for a computer to provide optimum values for all the key design parameters of a communications link.

The methodology forms a basis of analysis which uses as gross inputs 1) mission objectives and requirements and 2) detailed descriptions of communication constraints and components. These include such components as transmitter power sources, antennas, detectors, etc.

IMPLEMENTATION OF DESIGN CRITERIA IN A USEABLE FORM

The Communications Design Criteria has been implemented in a computer program with an easy to use buffer language called COPTRAN. This language enables a user, without a knowledge of computer programming, to obtain optimized solutions to space communications problems.

The optimized communication methodology or design criteria mentioned in the previous topic contains a great amount of detail and requires a large amount of calculation to produce optimized values. Therefore the problem has been implemented into a computer program using FORTRAN IV language. Solutions using this program provides optimum values of the four major system parameters* and values for all the other related communications hardware. This is a versatile computer program which provides optimized values for the communications system. However one further step has been taken. The program, written in FORTRAN IV language, requires a user familiar with this language to obtain optimized results. Therefore a buffer language called COPTRAN (Communication OPtimization program TRANslator) has been developed.

To operate the Design Criteria optimization program using the COPTRAN language involves answering a few simple questions which are written in the language of the user. For instance one question is: "What is the transmission range?" Following this question is a choice of four six letter mnemonics and their meanings. One of these, RANMAR, may be chosen to tell the COPS methodology through the COPTRAN buffer language that the range (RAN) is a Mars (MAR) distance, nominally 10^8 km.

Similar simple questions, again using a multiple choice listing of mnemonics, are answered for such topics as the modulation type, the type of optimization desired, the type of output desired, etc.

The user may also use standard sets of data for the inter-relationship of transmitter cost to power, etc. (burden relationships). Or if the user desired, he may change one or all the nominal constants, thus superceding the stored values.

The mnemonic answers and data values that are selected by the user to describe the problem to be solved are written down by the user on a simple COPTRAN form. This form is then used to punch computer cards, one card per mnemonic or data value. The cards become part of the COPTRAN program and are batch processed by a computer.

The computer results are returned to the user either as a line printout or as Cal Comp plots.

The figure summarizes the steps in obtaining optimized communications parameters using the COPS computer program with COPTRAN language.

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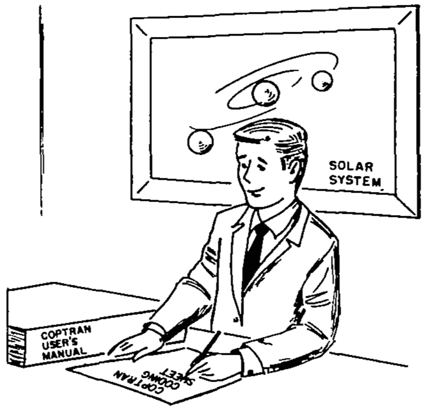
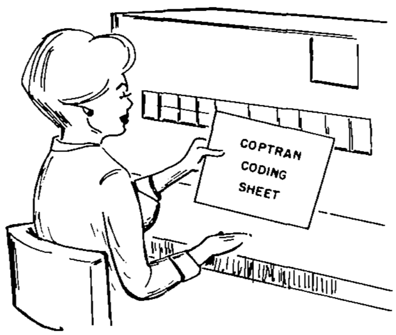
*Transmitter power and antenna gain, receiver antenna gain, and receiver field of view.

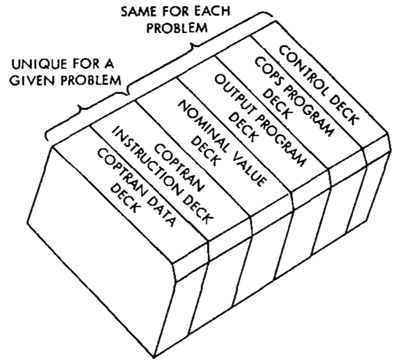
USER AND HIS REQUIREMENTS



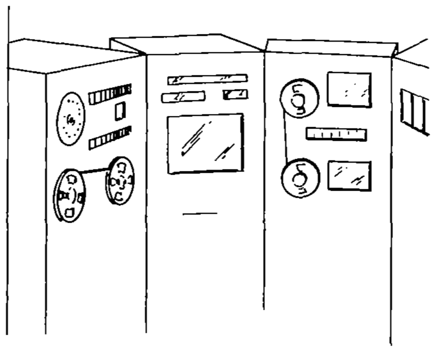
USER PUTS HIS REQUIREMENTS
ON COPTRAN SHEETS



CARDS PUNCHED FROM COPTRAN CODING



USER'S PROBLEM IS ASSEMBLED
AS A CARD DECK



PROGRAM RUN BY COMPUTER

OUTPUT RETURNED TO USER

COPTRAN Programming

MICROWAVE AND LASER SYSTEMS COMPARED USING DESIGN CRITERIA

Microwave systems are superior to laser communication systems up to a bit rate of about 1 megabit/second. At data rates higher than this laser systems are both lighter and less expensive for a given bit rate than microwave systems.

The design criteria* developed during this contract can be used to compare laser and microwave systems where each system configured in an optimum way. The comparison is made on the basis of weight and cost where the optimization procedure selects communication parameters which produce the lightest or least expensive communications hardware. Two systems (e.g. a laser and a microwave) can be designed by this means and the results compared. This has been done for 4 different systems and the results are given in Figures A, B, C and D.

The four systems are 1) a radio system with a carrier frequency of 2.3 GHz, 2) a radio system with a carrier of 10 GHz, 3) an optical system with a carrier wavelength of 10.6 microns, and 4) an optical system with a wavelength of 0.53 microns. These frequencies have been used and have been considered widely for space communications.

The design criteria, embodied in a computer program called COPS, is capable of providing a great variety of outputs. Some of this flexibility is shown and all is described in Appendix B of volume II. The desired output for the comparison given in this topic was the overall weight and cost of the spaceborne communications hardware. Thus the figures are, in a sense, a summary of many designs (5 were made for each decade of bit rate) where the design is summarized in terms of cost or weight.

The four figures illustrate the combinations of the cost and the weight optimization procedure with the two sets of burdens, estimated 1970 burdens and estimated 1980 burdens.**

The figures plot weight and cost against the product of receiver signal to noise rate, S/N, times bit rate, R_B. The curves were actually calculated for a signal to noise ratio of 10. The general form of (S/N) (R_B) is quite valid for all cases except the 0.53 micron laser case. Here the curve has been calculated using a bit error rate of 0.001 with S/N = 10 and really is valid only for such a value.

Several earth station parameters were fixed (see the table) for the various frequencies and some were specific requests from the Program Director, Dr. Kalil.

As may be expected, a cost optimized system does not provide the lightest system nor does a weight optimized system provide the least expensive system. For this reason weights and costs respectively have been indicated on the cost optimized and weight optimized curves of the comparison.

*This criteria is described extensively in Appendix A of Volume II of this report.

**Burdens relate the communication parameters to cost and weight.

As may be seen from all the figures, optical systems are both lighter and less expensive than radio systems at very high bit rates while radio systems are superior by both criteria at lower bit rates.

Table of Communication Parameters Used in the Link Comparisons

	Wavelength			
	13 cm	3 cm	10.6 microns	0.53 microns
Receiver Diameter	64 meters	64 meters	4 meters	1 meter
Receiver Noise Temperature	27°K	60°K	--	--
Receiver Aperture Eff.	55%	35%	90%	80%
Transmitter Aperture Eff.	70%	60%	90%	90%
Sky Background*	--	--	2×10^{16}	2×10^{16}
Detector Quantum Eff.	--	--	0.5	0.2
Optical Filter Bandwidth	--	--	--	10^{-3} microns
Transmitter Losses	1.25 db	1.25 db	1 db	1 db
Receiver Losses	4.5 db	4.5 db	2.2 db	1.5 db
Atmospheric Losses	0.2 db	0.2 db	1.0 db	1.0 db

*Photons/(sec-cm^2-micron-steradian)

MICROWAVE AND LASER SYSTEMS COMPARED USING DESIGN CRITERIA

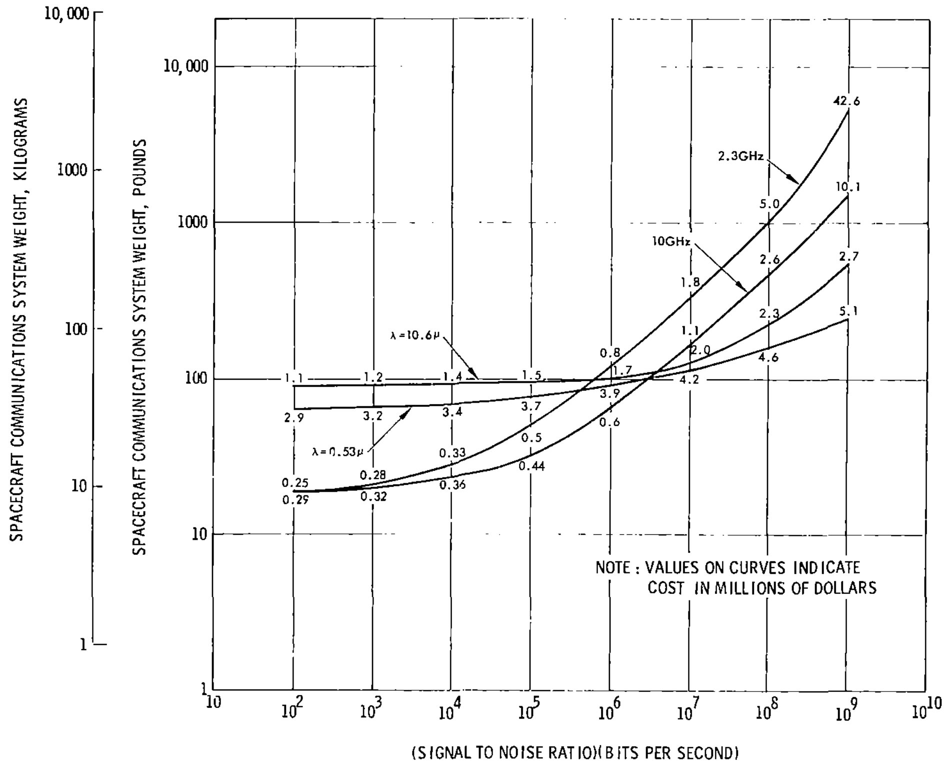


Figure A. Spaceborne Communications Systems Weight as a Function of Performance for Weight Optimized Systems Using 1970 State of the Art and a Mars range, 10^8 Km

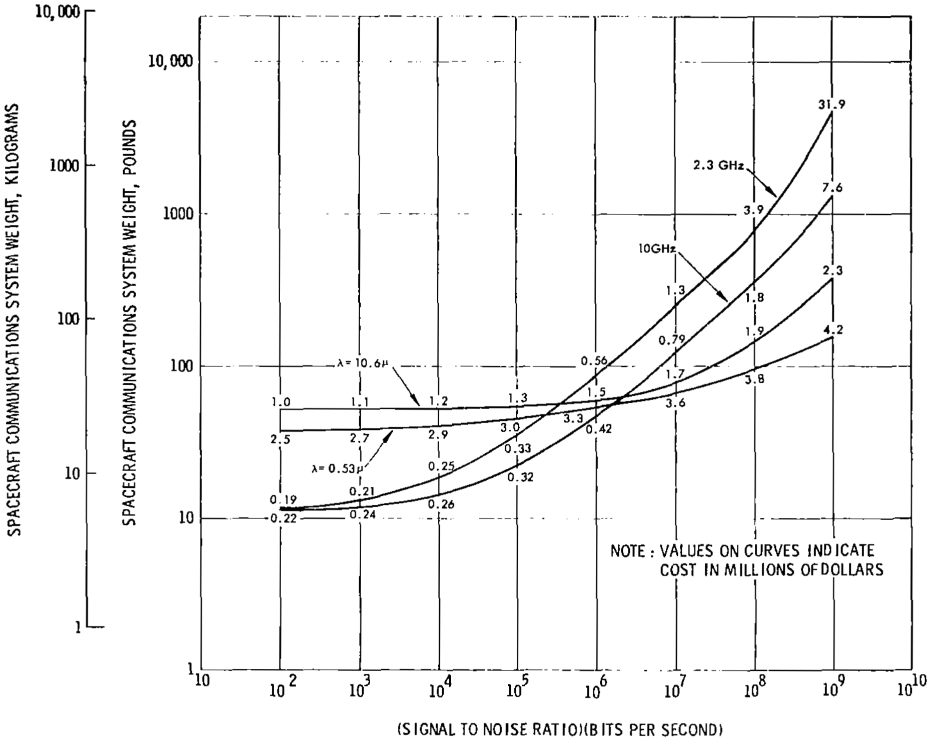


Figure B. Spaceborne Communications Systems Weight as a Function of Performance for Weight Optimized Systems Using 1980 State of the Art and a Mars Range, 10^8 Km

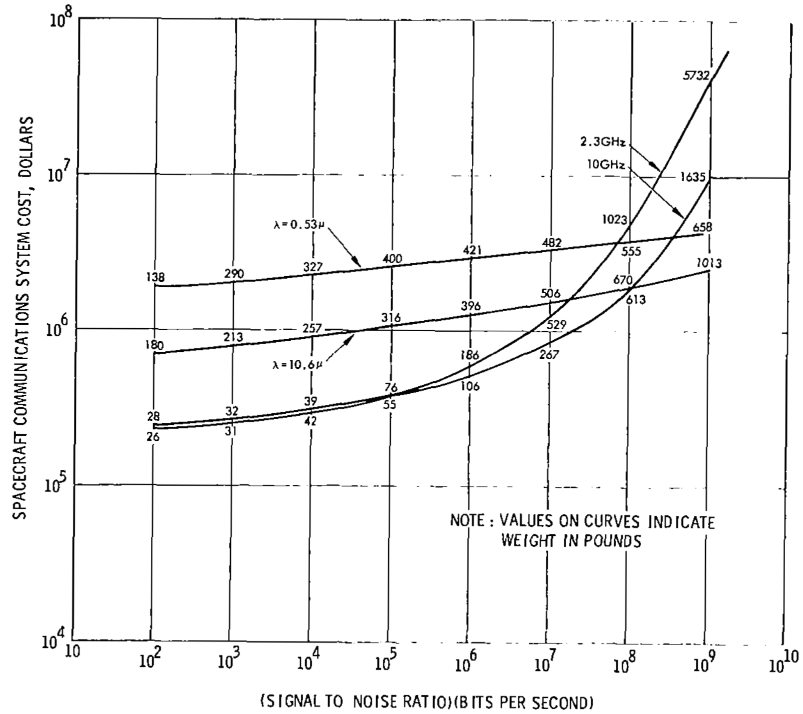


Figure C. Spaceborne Communications Systems Cost as a Function of Performance for Cost Optimized Systems Using 1970 State of the Art and Mars Range, 10^8 Km

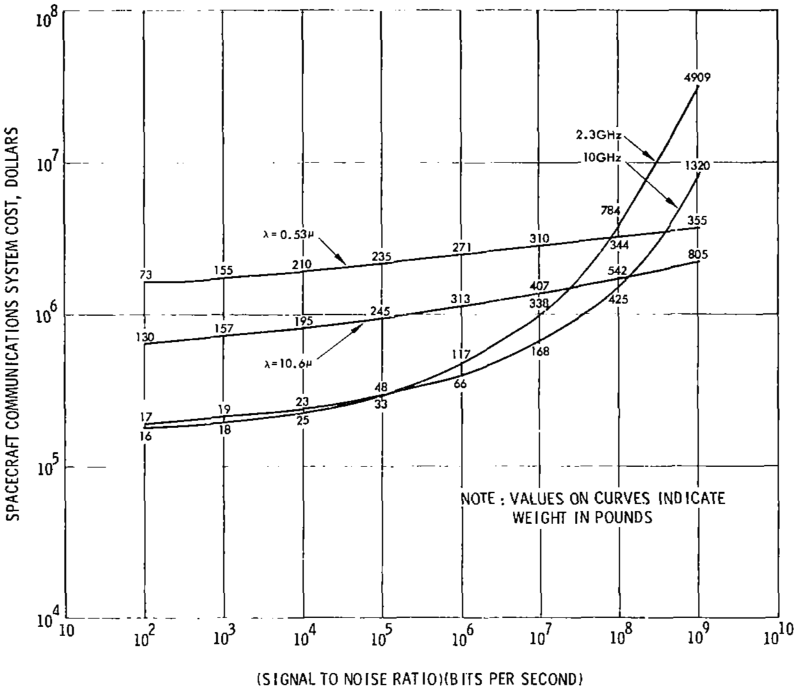


Figure D. Spaceborne Communications Systems Cost as a Function of Performance for Cost Optimized Systems Using 1980 State of the Art and Mars Range, 10^8 Km

SUMMARY OF EARTH RECEIVING NETWORKS

Several radio networks have been developed for space communication; DSN, MSFN and STADAN. However there is no optical network to utilize the superior performance promised by optical communications for certain missions.

There are three major ground networks for spacecraft radio communications. These are the Deep Space Network, DSN; the Manned Space Flight Network, MSFN; and the Satellite Tracking and Data Acquisition Network, STADAN. These three networks are briefly described below.

DSN

The Deep Space Network (DSN) is a precision tracking and communications system capable of providing command, tracking, and data acquisition from spacecraft designed for deep space exploration. Although it is designed for use in deep space exploration, the DSN may be used with other types of missions, e.g., manned missions, where its capabilities can be used to advantage.

The DNS is comprised of nine Deep Space Stations (DSS) clustered in three Deep Space communication complexes (DSCC) and called the Deep Space Instrumentation Facility (DSIF), an intersite communications network called the Ground Communications Facility (GCF), and a Space Flight Operations Facility (SFOF) located in Pasadena, California.

MSFN

The Manned Space Flight Network (MSFN) provides tracking, communication, telemetry, and voice transmission in real time between the manned spacecraft and the Mission Control Center. This capability is provided to MSFN stations by: the Unified S-Band System (USBS), a VHF telemetry and voice system, a UHF command system, and by C-Band and S-Band tracking radars. The performance of a typical MSFN station is influenced by the strategic location of the station for mission coverage and the communication between the station and the mission control center.

STADAN

The primary purpose of the STADAN is to receive data from scientific satellites and to produce tracking information for orbit computation. Most of the equipment in the STADAN has been designed for use by many programs, with emphasis on quick adaptability to the differing requirements of several simultaneously-orbiting spacecraft. Most programs do not require data from all STADAN stations, so the specific capabilities of each station have been tailored to differing levels of performance.

The STADAN consists of three major systems: the Data Acquisition Facilities, Minitrack, and the Goddard Range and Range Rate System. The Data Acquisition Facilities (DAF) is equipped with multi-frequency, high gain antennas and its capability of handling large quantities of data at high rates exceeds that of the standard Minitrack systems.

The second major functional system, Minitrack, has been used to track all U. S. satellites which have suitable beacons, since the beginning of the space program. In addition to its tracking functions, the Minitrack system has the facilities for receiving telemetry data in the 136- to 137-MHz and 400- to 401-MHz bands.

The third major system of the STADAN is the Goddard Range and Range Rate Tracking System which complements the Minitrack network by providing improved tracking data for space probes, launch vehicles, and satellites in highly elliptical orbits.

A particular STADAN station may have any combination of the above systems, and the specific configuration of the system will vary depending on the cumulate requirements placed on the station.

Optical Ground Sites

At present there are no ground networks for optical communications. There are, however, a few facilities which are being used for laser earth to space transmission and for making measurements needed to design such links. These facilities include 1) a telescope facility and Goddard Space Flight Center which has successfully performed laser ranging experiments to a low altitude satellite; 2) a lunar ranging site in the Catalina Mountains of Arizona which has measured range to the moon using a retroreflector placed on the moon by the Apollo astronauts; and 3) atmospheric experiments being conducted by the Smithsonian Astrophysical Observatory for NASA at Mount Hopkins.

Clearly the radio receiving facilities are well developed, are performing with manned and unmanned spacecraft, and are being developed as required. Conversely, optical communications facilities are in an early experimental phase. Since optical communications do show clear advantages over radio communications for some missions (missions requiring exceptionally high data flow, e. g. , a planetary orbiter mission).* There is therefore a need for implementing an optical communication network.

Ground Stations

Ground stations for optical space communications may take one of two basic forms. The first is an optical receiving site which receives the laser beam directly from the space borne transmitter. With such a receiving implementation it is virtually impossible to obtain 100 percent contact with the spacecraft due to attenuation of the laser signal by clouds. While 100 percent coverage is very difficult, a number close to 100 percent can be achieved by careful placement of the surface stations and by having more than one station receiving simultaneously for back up.

A second basic form for an optical receiving system is that of a satellite, preverably in synchronous orbit, which receives the laser signal, detects it, and retransmits the data to a surface station using a radio link. Such an implementation, while more complex, can provide 100 percent coverage.

*See previous topic.

OPTICAL SITE CONSIDERATIONS

Earth receiving sites for optical communication should favor a convenient site for a pilot station and favor a site with inherent optical performance for an ultimate configuration.

Optical communication can provide high data rate performance for less cost or weight than radio communication for certain missions. This conclusion, documented in other portions of this final report, has given impetus to the development of an optical communication ground network. It is the purpose of this topic to note the major considerations for the placement of stations for such a network.

Function of Optical Communications Earth Site

An optical communication site is not intended to perform all the functions that are presently performed by the radio networks. An optical link is best used as a specialized data link capable of transmitting very high data rates over planetary distances. It is anticipated that the existing radio links will continue to perform functions of trajectory determination, command, and reception of telemetry data from spacecraft status monitors. The choice of an optical site must then consider the proximity to suitable radio facilities as well as conditions suitable for optical communications.

The implementation of an optical facility entails a large expenditure and certainly should be done in phases such that the knowledge obtained with early sites and configurations may be used in later designs. Such a pilot site would be used to determine atmospheric affects upon wide band data transmitted via a laser, affects upon seeing as a function of site surroundings, i. e., mountain side position, plain position or lake mounted position; and statistical affects of the atmosphere as a function of weather patterns, elevation angle and time of year. The affect of the atmosphere upon defraction of the laser beam which acts as a beacon for the spacecraft may also be examined.

In addition to these environmental bounds, mission functions such as the interface between the optical data reception and the world wide communication networks may be exercised.

The pilot station may also carry out experiments with presently planned optical space communication experiments such as the ATS-F & G CO_2 laser communications experiments.

The ultimate goal of an optical communication network would be to function the receiving site for extremely high performance communications links. The links of this type are exemplified by a reconnaissance spacecraft orbiting Mars. Here very high data rates can be provided by the imagery sensors at planetary ranges. Additionally, if mapping the entire planet is desired, it is possible that there would be periods of time when data interruption would not be objectionable since the same imagery could be obtained on a subsequent orbit. This consideration of non-continuous data, reduces considerably the number of earth stations that would be needed. Further it would reduce the emphasis placed upon an orbiting relay sateilite, where the relay satellite receives the optical signal and then relays it to earth on a radio link.

Site Considerations

There are two basic considerations in site selection: convenience and technical suitability.

Convenience relates to the proximity to radio networks such as the Deep Space Network or NASA centers or contractor facilities. In addition to these there are the basic needs of roads, service buildings etc. which must be considered.

Relative to technical performance, the largest single variant is the atmosphere and its constituents. Clearly optical observatory sites are chosen for many of the characteristics needed by laser communications such as a high elevation, having a minimum amount of cloud cover, background light and for generally good seeing. There are additional constraints or degrees of constraints that are required by laser communication. These include the atmospheric defraction, the coherence length and the daytime atmospheric background. Thus it may well be that existing astronomical sites are not the best overall choice for a laser communication.

Conclusion

The need for a development of a laser communication receiving network is based upon the higher performance of lasers in certain missions. The development of a network must be sequential as the knowledge of the desired site characteristics and configuration is developed. Based upon these considerations and upon site location considerations of convenience and technical performance, a pilot site near the STADAN headquarters, the Goddard Space Flight Center, is suggested. Such a site is convenient and can operate with such experiments as the ATS-F and G laser communication experiment.

An ultimate network would have the primary United States sites located in the southwestern portion of the country, near the Goldstone, California DSN Station. Other possible worldwide stations are listed in the table.

Selected Sites for Optical Observations

	Longitude (Hours:Minutes)	Elevation (ft)
National Observatory of Argentina Bosque Alegre Station, Argentina	+4:18	4,100
Radcliffe Observatory Pretoria, South Africa	-1:53	5,060
Nizamia Observatoria Hyderabad, India	-5:14	1,820
Mount Stromlo Observatory Canberra, Australia	-9:56	2,520
Mauna Kea Peak Hawaii	10:35	13,796

OPTICAL STATION NETWORK - PROGRAM PLAN

A two phase program plan is presented which outlines the construction of a pilot station and three operating stations for an optical space communications network.

The orderly development of an optical ground network can be done in two phases, an experimental phase and an operational phase. The rationale for such a program was described in the previous topic and the time phasing is presented below and in Figures A and B.

Phase I - Experimental System Development

Figure A is a suggested program plan for the development phase of an optical network. It is the purpose of this phase to develop a ground station design suitable for the operational system, to determine suitable site environmental parameters, and to select sites for the operational network.

In order to accomplish the goals of Phase I, a four part program is suggested: 1) station design and test, 2) optical station integration with the radio network used for scientific satellite testing, STADAN, 3) site atmospheric testing, and 4) operational system site selection. The STADAN radio network was selected as a companion network for the experimental testing since it is likely that space to earth testing would be accomplished using near-earth scientific satellites. Since the STADAN central control is the Goddard Space Flight Center, it is further suggested that the experimental optical site be near GSFC to facilitate integration with STADAN.

Site atmospheric testing will be conducted during the majority of the Phase I period. This will provide data such as optical coherence length, seeing, temperature gradients, etc., and possibly correlation of these data to commonly recorded meteorological data for a period greater than one year.

With the atmospheric data it will be possible to analyze prepared sites for the operational system and to plan the operational system and the Deep Space Network (DSN) interface.

It should also be noted that in those instances where manned vehicles use laser communication for deep space missions, e. g., manned landing of Mars, that the DSN may temporarily become a part of the manned Space Flight Network (MSFN). Thus the operational network site solution task includes an interface study between the DSN/MSFN.

Phase II - Operational System Development

The time phasing for the operational system development is indicated in Figure B with a summary of Phase I. Phase II of the optical station network begins as soon as Phase I is completed. The summary program plan indicates three sites which are completed four and one half years after the initiation of Phase I. The construction period for the first of these sites is somewhat larger than the second and third to allow for initial contingencies.

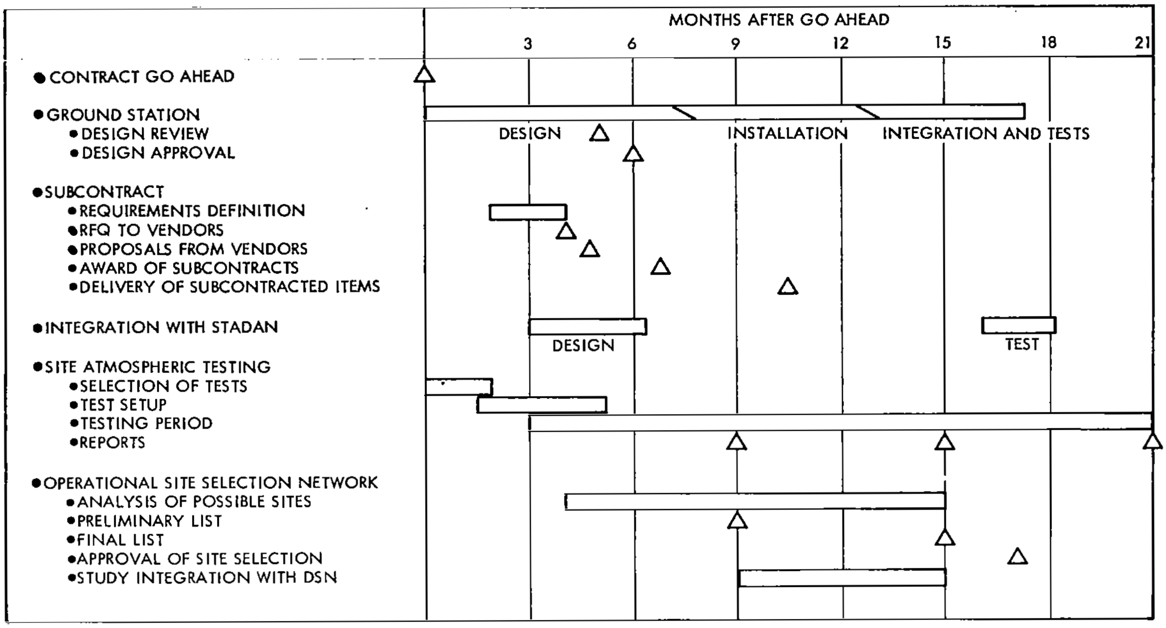


Figure A. Phase I Optical Station Network - Program Plan

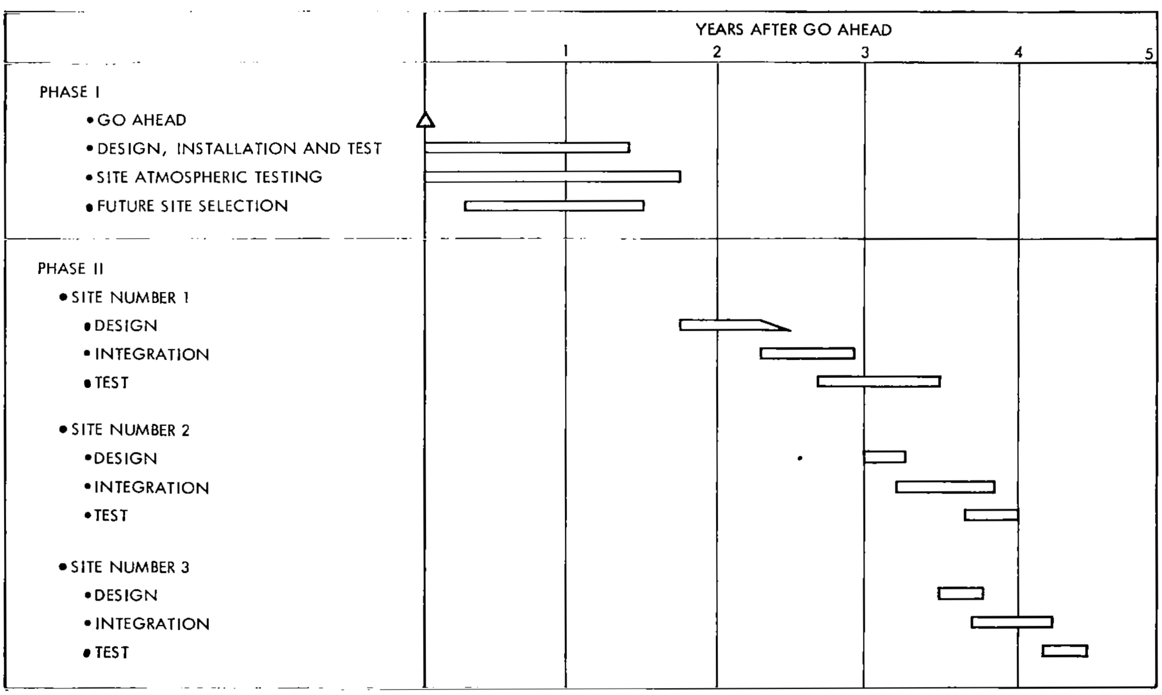


Figure B. Optical Station Network - Summary Program Plan