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INFORMATION TRANSFER SYSTEMS IN SPACE COMMUNICATIONS

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SUMMARY

A comprehensive survey and study of the basic parameters of information transfer systems for space communications is presented to familiarize systems checkout engineers with the state-of-the art and trends in this field because it now appears that on-board systems will be depended on for checkout performance and checkout data transfer. Both current and anticipated requirements for communication systems are considered. Some of the problems that exist in space communication are presented along with a general review of present communication systems, their capabilities, and their limitations.

It is concluded that present space communication systems are adequate for all communication needs of lunar missions, including transmission of visual and audio channels and tracking, telemetry, and command functions. They can also satisfy the basic communication needs of unmanned planetary missions to Mars, and, in the near future, to Venus, provided the attitude-control system of the space vehicle can keep the vehicle's antenna accurately pointed at the Earth. The increased capabilities expected by the end of this decade should make adequate space communication systems possible for most predicted communication needs of the future.

SECTION I. INTRODUCTION

A survey was conducted to review present space communication systems and systems anticipated for the 1966-1970 period. The results of this review are summarized in this report. It is not written for the communication engineer but to familiarize systems checkout engineers with the capabilities and limitation of information transfer systems used in present space communication operations. The survey covers communications between objects orbiting the Earth or the Moon, objects in transit from the Earth to the Moon, and objects in transit from the Earth or from lunar points or orbits to the planets of Venus and Mars. Equipment, power, information transfer forms, flexibility, trade-off parameters, and similar factors of space communication systems are covered in the survey.

Because the scope of the survey is broad, no detailed treatment of specific systems or components is given. Detailed consideration of factors and techniques that can improve communication system performance is given to show a proper perspective of the subject.

The space communication system functions of tracking, trajectory determinations, telemetry, command, and television are briefly considered. The aspects of space communication system requirements of most interest to the systems checkout engineer (i.e., maximum information transfer, long life, and reliability) are also discussed. Signal propagation and detection aspects are considered in enough detail to allow an understanding of the physical and geometric factors that determine some basic system parameters and, at the same time, determine the optimal system capability under a given set of conditions. This portion of the report is followed by a brief account of information theory as applied to space communication systems and accounts of modulation systems and encoding, particularly descriptions of power-efficient codes. Possible improvements in system capability and performance are explored in some detail in the areas of spacecraft directional antennas, ground antennas and ground stations, spacecraft transmitter power, telemetry systems, and optical communication systems. The survey ends with a predicted increase in the capabilities of space communication systems as estimated by the Jet Propulsion Laboratory. A rather extensive list of references, with appropriate comments on their scope and content, is included in the report.

SECTION II. FUNCTIONS OF SPACE COMMUNICATION SYSTEMS

The capabilities of a communication system designed to be used in spacecraft on deep space missions can be divided into four broad categories: (1) determination of the exact location and course (Tracking and Trajectory Determination), (2) measurement of the performance of vital components or functions (Telemetry), (3) transmission and reception of vital commands (Command), (4) visual transmission and reception of performance or observations (Television).

The first three functions are and will continue to be vitally important to any spacecraft mission; the last one is important for the Apollo and follow-on lunar exploration programs, the unmanned exploration of Venus and Mars, and possibly for the unmanned exploration of the planets Mercury and Jupiter later in the century.

Readers will find additional information on functions of space communication systems in references 1 through 13. For design philosophy and possible concepts in space communications, see references 14 and 15. Reference 16 gives methods for comparison and evaluation of communication systems, and reference 17 deals specifically with communication problems between Earth satellites.

Tracking and Trajectory Determination

At this time, radio frequency tracking provides the only method of securing data for precise, deep-space trajectory determination. At the beginning of the mission, optical observation also provides data for trajectory determination. Precise trajectory knowledge is important for a correct interpretation of scientific data, for determining the direction and magnitude of any correction required in midcourse, and for establishing spacecraft antenna pointing data for efficient operation of the communication system.

Doppler frequency shift, range, and ground antenna pointing angle are the three basic measurements taken for trajectory determination. Doppler and range measurements usually require a cooperative spacecraft, while the antenna pointing angle is a ground system measurement. Accurate Doppler information is obtained from a coherent two-way system, where a flight transponder coherently tracks the incoming radio frequency (rf) carrier received from the ground station and radiates back a carrier whose frequency relationship to the received carrier is set and is known. Such a system permits an accurate count of the Doppler shift by the ground receiving station; and hence,a spacecraft velocity determination that is highly accurate (of the order of one foot per second or less).

For accurate ranging at interplanetary distances, the signal round-trip propagation time is measured by correlating pseudo-random codes. This propagation time (time delay) is then a measure of the distance to the spacecraft. For missions near Earth the signal-to-noise ratio of the communication link is sufficient to allow the ranging codes to be received and relayed by the transponder directly. At interplanetary distances, however, as the signal-to-noise ratio degrades, the spacecraft must detect, reconstruct, and retransmit the ranging pseudo-random codes. More advanced ranging systems not only correlate the codes, but also correlate the phase of the code carrier and the rf carrier, and thus provide a greater vernier for the reading of range.

The ground antenna pointing angle is especially valuable in the early portions of the trajectory for a quick determination of the estimated trajectory. This measurement is also valuable for operational purposes in transferring control from ground station to ground station and in predicting tracking programs.

The information bandwidth required for tracking a spacecraft coasting in space is very small, since the motion of the spacecraft is completely predictable if only the basic constants that determine the initial conditions are accurately known. A tracking operation, even of long duration, can be considered as a progressive refinement of the initial constants; hence, an interplanetary spacecraft may need to be tracked only once or twice a day for a few minutes at a time. Normally, tracking exercises are carried out by a tracking station, or stations, supplied in advance with the predicted spacecraft position and velocity; thus, their function usually is to determine small errors in the predicted values.

Telemetry

The telemetry subsystem of the communication system provides the link for the transmission of a large variety of scientific data taken by the spacecraft in flight and at planetary or lunar approach. It also receives and transmits engineering data which permit the evaluation of spacecraft performance of certain operations to be conducted during flight. Such data also permit failure analysis in case of equipment malfunction. In the future, it may be possible to use the telemetry subsystem for such functions as automatic checkout and collection of failure prediction data.

Widely varying demands are placed on the radio communication system by the telemetry of data, and these demands depend upon the specific mission to be accomplished. For example, the Pioneer V spacecraft, which was tracked over 20 million nautical miles[1], transmitted telemetry data with an information bandwidth of a few Hertz at a rate of only one bit per second; but direct television signals from the moon or planets, or TV relay via a communications satellite, would require bandwidths of several megahertz.

The primary function of the telemetry subsystem is to provide the capability of transmitting the maximum amount of information from any point in the trajectory. Usually, the information contains much redundant data among the useful data, i. e., measurement data that are of no interest at a particular time and data of low priority that are using link capacity and thus compromising data of higher priority. To transmit only useful information, the data handling system requires extreme flexibility in programming and routing capabilities and must incorporate, if required, adaptive techniques, data compression techniques, and data storage devices. These techniques would, in the future, make it possible to attain a more efficient use of the available power, which is generally of premium importance in space missions. To have the maximum amount of data available at any point in the trajectory,

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[1] The word miles, used throughout this report, refers to nautical miles, unless otherwise specified.

the distance over which telemetry data must be transmitted should be considered. As the distance increases from a few hundred miles at the beginning of the mission, to tens or even hundreds of millions of miles as the spacecraft approaches its destination planet, the telemetry bit rate of the link would decrease in excess of 1,000,000 to 1. To provide the maximum data rate at any point in the trajectory under these varying conditions, the telemetry encoding system must be mechanized so that the data rate can be changed by either program or command, in appropriate increments. The encoding method to be selected for interplanetary spacecraft should be one which allows the data rate to be changed with a maximum of data reliability, using a minimum of hardware, and achieving maximum communication reliability.

Command

The command link provides a means of controlling appropriate spacecraft functions. The command functions may be divided into two broad categories;(1) providing on-off control to be executed in real time,and (2) providing a means of relaying information,of varying work length, stored in the spacecraft control system or data handling system.

The requirements for transmission of data over the command link are radically different from the requirements for transmission of the telemetry data. The required transmission rate for command data is quite low, which permits the use of a relatively narrow bandwidth. Also, because the command words occur randomly and quite infrequently, the word synchronization problem is easier, but the accuracy requirement is severe compared to telemetry. Accuracy for the command link is less than one erroneous bit per 100,000 bits transmitted, while the permissible error rate in the telemetry link is one or two erroneous bits per 1000 bits transmitted. In contrast with telemetry detection and decoding equipment, in the spaceborne command system,the detection and decoding must be done by remote control with equipment that must work reliably in the spacecraft environment, and function properly without the aid of an operator.

Television

Television communications are a requirement for certain space missions such as unmanned lunar and planetary explorations. Television pictures would complement information about the physical characteristics of the celestial body which the scientific instruments of the spacecraft would provide.

Studies performed by the Jet Propulsion Laboratory indicate the complete feasibility of real-time television from the moon using presently available techniques and equipment. For example, using a signal-to-noise ratio of about 10 decibels and efficient information coding -- like pulse code modulation -- some ten frames per second could be transmitted on a bandwidth of 100 megacycles. In this Moon-to-Earth system the spacecraft antenna beamwidth is broad enough to illuminate the whole Earth, avoiding the necessity for the vehicle antenna to track a moving ground station. Also, the ground antenna beam-width of the Earth-to-Moon link is broad enough to cover the Moon-circling vehicle while the beam is aimed at the center of the Moon's face. The systems envisioned for a lunar or Mars lander employing television are slightly more complicated.

Examples of television in space communications are furnished by the Tiros, Nimbus, and Telstar Satellites, the Ranger and Surveyor Moon Programs, the Mariner Program, and the Soviet Orbital Programs.

In manned space missions, television transmission from the spacecraft to Earth may be important as an additional means to check the well-being of the astronauts. Also, for long-duration space missions, transmission of televised entertainment and news may be needed to bolster the morale of the crew.

SECTION III. REQUIREMENTS OF SPACE COMMUNICATION SYSTEMS

Space exploration demands communication system capacity and reliability far in advance of that previously achieved in terrestrial endeavors. Although the new techniques used for space communications are based on their predecessors, (microwave transmission, radio-astronomy, radio-telemetry, frequency modulated systems, etc.), it is necessary, because of economy and data-taking limitations, to restrict as much as possible the flow of data from manned and unmanned space vehicles. On economic grounds, prime energy, weight, and size are presently limited. Basic limitations on data-taking are set by the error probabilities introduced by signal-to-noise ratios in transmission, by calibration errors, by insufficient knowledge of the effects on materials of the space environment, and by limited data processing capability at the base stations (this capability, and the amount of data flow, should nearly match).

Three factors can be singled out for special consideration in space communication systems: (1) maximum information transfer, (2) long life, and (3) reliability.

Maximum Information Transfer

In any communication system, the kind and amount of information to be transmitted is of the greatest importance. The kind of information depends largely upon the source, and may be varied by appropriate selection of the form of the message generated. The amount of information must be adjusted to the channel capacity of the communication system and, for many scientific and technical purposes, may be varied without much loss in the utility of the experiment or measurement. For example, in the case of a Geiger-Mueller counter, appropriate scalers may be used which result in a final output (counting rate) which is a small but known fraction of the input counting rate. In addition, this particular system offers the possibility of varying the output rate easily by switching the number of divider stages. When there is a requirement for transmitting pictures, the effective bandwidth and information rate may be reduced by sampling techniques.

Also of importance is the information obtained from the various equipment monitors in the vehicle. Usually, the information rate from these monitors is very low, so it is possible by sampling and subcommuting to transmit a large number of measurements over a very narrow bandwidth.

These examples show the use of relatively simple means to adjust the information data rate of physical measurements to the available channel capacity of a space communication system. In other words, the communication system objective is to achieve the maximum information transfer by means of the available channel.

There are cases when the coding techniques just explained for efficient channel utilization cannot be applied. For instance, real-time voice channels would require large capacity circuits, because the possibility of reducing bandwidth by encoding the spoken word is very limited. Similarly, real-time television channels would require even larger bandwidths. Besides these, there are cases in a space mission where large bit rates are required for very short times; for example, at the terminals of a space voyage, either at takeoff or at landing, it may be necessary to transmit simultaneously large amounts of information. The energy per bit of information is the same as for slow transmission, but the information rate and transmitted power would be very large. For these purposes one solution is to provide emergency channels, or one-shot, high-peak power transmission. A hard landing on the moon may require such transmission for a fraction of a second, while a soft landing may permit many seconds or even minutes of such high information rate transmission [18, 19].

Long Life and Reliability

Long life expectancy and reliability are vitally important factors in flight equipment for long-duration space missions. A lunar mission has a duration of a few days; a flight to Venus, however, requires more than three months. Missions to Mars would require between six and eight months, while the flight time to Jupiter or to Saturn would be between two and three years. In order to accomplish these missions successfully, the equipment must operate continuously under extreme variations in environmental conditions over these periods of time. When human life is at stake, the requirements may be even more stringent.

Calculations using any of the common statistical distributions, such as the exponential, show that for a required operating time, the mean time to failure of the device must be of an order of magnitude greater than the operating time required in flight, if the device is to exhibit a high probability of success in its mission. This problem is familiar to those people developing weapon systems with rather short operating times. It becomes an even greater problem when dealing with the mean time to failure requirements for any long-duration space mission. These missions have to be achieved with a high probability of success and with little or no opportunity for maintenance. Means and techniques that have been suggested to achieve these results are discussed in the following paragraphs [20 through 24].

The high reliability required of the equipment used for complex long-duration space missions, especially of the manned type, imposes stringent requirements on the quality of the components employed, as well as on the appropriate design and handling of the equipment. This is especially true of the communication systems with which we are concerned in this survey.

Much remains to be done to achieve greater reliability before a high probability of success in the space mission can be achieved. Before indicating the steps that have been suggested to achieve the necessary reliability, it may be useful if we list most causes of failures. Assuming that the user has properly specified the reliability requirements, these causes can be relegated to three main areas: (1) improper design, (2) inadequate quality control and manufacture, and (3) improper field handling [20].

Within these categories the reasons for failures are:

Improper Design. The most frequent examples of improper design are:

(a) Improper use of parts and materials

(b) Failure to take into account all of the environmental or operational conditions under which the equipment must work

(c) Failure to use proper safety margins

(d) Failure to verify, by environmental and other tests, that the design measures up to its requirements

Inadequate Quality Control and Manufacture. Some of these principal types of error are:

(a) Incorrect assembly

(b) Process out of control

(c) Substitution of improper parts and materials

(d) Insufficient training of personnel, or use of personnel of a low level of skill

(e) Over-emphasis on schedules

Improper Field Handling. The most frequent examples of improper field handling include:

(a) Improper use of equipment

(b) Failure to provide proper written instructions

(c) Failure to follow written procedures

(d) Exposure of the equipment to unfavorable environments, such as the natural elements

(e) Dropping, up-ending, and otherwise rough handling of the equipment

This list does not exhaust all the reliability pitfalls; it merely indicates some of the most common causes of failures.

Reliability Improvement

Steps suggested to achieve the necessary reliability [20, 24] are as follows:

Development of Realistic Reliability Analysis and Synthesis Techniques. In the field of reliability, there now exists a wide gulf between the mathematicians and statisticians on one side and the engineers who work on hardware on the other. This gap must be closed by some combination of mathematical and empirical techniques which will provide a reasonably accurate, useful method of estimating the reliability of current systems which will be useful in planning future systems from the standpoint of reliability.

Use of Components of High Quality. Continual surveillance and testing may be required to obtain and maintain a source of high quality components.

Standardization of Appropriate Subsystems and Logic Modules. By standardizing appropriate subsystems and logic modules, a great deal of engineering talent can be devoted to worst-case design and to the collection of reliable components in a particular subassembly. When this is accomplished, advantage should be taken of this effort by resisting the tendency to modify or make minor changes as may seem appropriate for any specific task.

Use of Redundancy to Advantage. Considerable improvement of system reliability can be achieved by using redundancy. There are probably as many cases of using redundancy to disadvantage as there are cases where redundancy has been used to advantage. An intelligent use of redundancy depends heavily upon the first step described above, that of adequate, accurate techniques to judge different configurations in terms of their reliability advantages.

SECTION IV. PROPAGATION ASPECTS

Space propagation and signal detection aspects are important in the design of space communication systems. Some of these items are as follows: design of ground antennas and space vehicle antennas, space attenuation, atmospheric and ionospheric absorption, polarization, interference, and doppler effect.

Ground Antennas

Most ground tracking stations use large parabolic reflectors as antennas because of convenience in design and also because the basic structure is useful over an extremely wide frequency range. Standard antenna theory shows that the gain, G, of a uniformly illuminated circular aperture of diameter, D, is given by

$$G = (\pi D/\lambda)^2 \tag{1}$$

for radio signals of wavelength λ, where G represents the power gain (on the antenna beam axis) over a hypothetical linear isotropic radiator.

In order to suppress side lobes, the feed to a parabolic reflector antenna is usually deliberately nonuniform, being tapered from maximum illumination at the center to zero at the edge. The efficiency of such antennas lies between 50 percent and 80 percent. If an efficiency of 50 percent is assumed, the gain equation becomes

$$G = 1/2 \, (\pi \, D/\lambda)^2 \tag{2}$$

for a normally designed antenna. In Figure 1, reproduced from reference 2, equation (2) is plotted for three antenna sizes.[1]

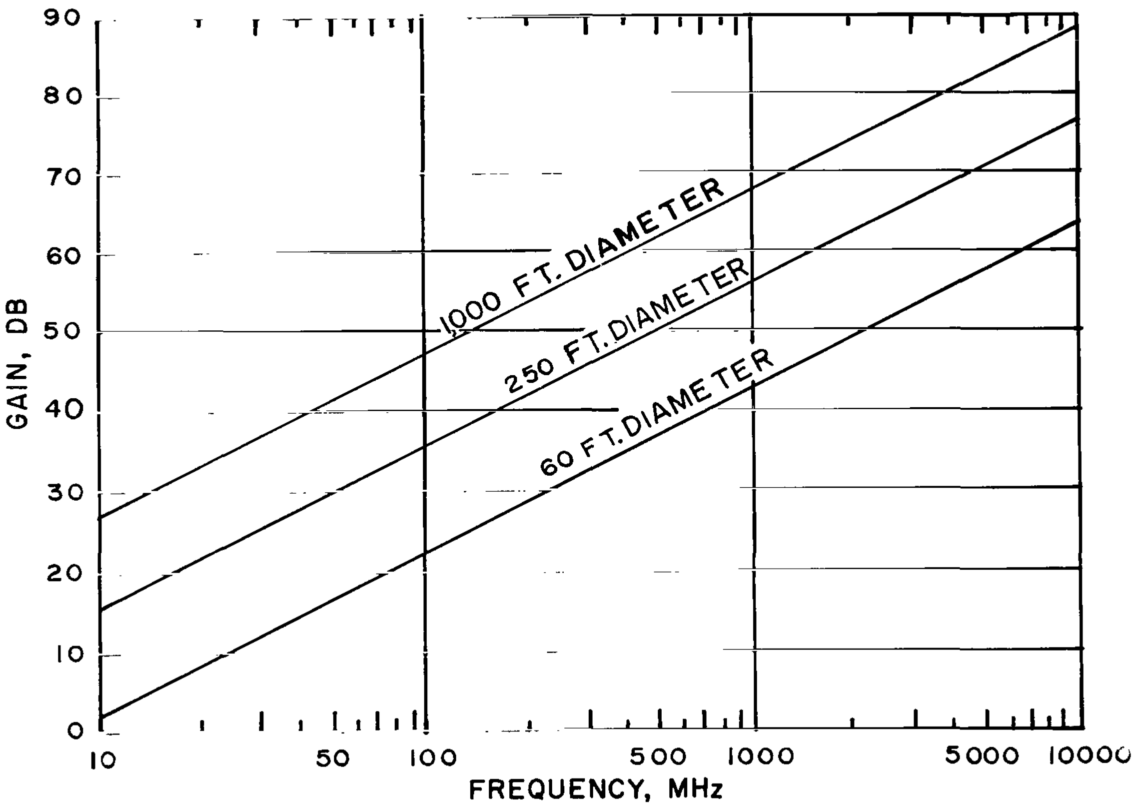

FIGURE 1. PARABOLIC ANTENNA GAIN VS. FREQUENCY

The beam angle θ in degrees— or more properly, the half-power beamwidth— of practical parabolic antennas with feed tapered from the center

[1]Throughout this report, the illustrations have been adapted using basic illustrations from references as noted.

to the edge of the "dish" is given in terms of its gain G by the approximate expression.

$$\theta \text{ (degree)} = 165 / \sqrt{G} \quad . \tag{3}$$

The area, efficiency, beamwidth, and gain of an antenna are the same whether the antenna is used for transmitting or receiving.

Space Vehicle Antennas

The simplest antennas used on space vehicles are quarter-wave stubs. The stub antenna is a length of rod one-quarter the wavelength ($\lambda/4$) of the carrier frequency. Four of these stubs placed in one plane and located 90 degrees apart can be made to provide a nearly omnidirectional, or uniform, radiation pattern.

All interplanetary probes launched to date have used spin stabilization, since the gyroscopic effect holds the payload spin axis fixed for a long time. For such probes, the antenna pattern should be symmetrical about the spin axis, and must be very broad. An antenna that satisfies these conditions is a dipole antenna whose axis is collinear with the spin axis of the probe. A dipole antenna has a doughnut-shaped pattern with a gain of 2.15 decibels on a plane perpendicular to its axis; however, a conservative value of zero decibels is often used to obtain the average gain over all of the visible angles except those near the dipole axis.

Vehicles that are attitude stabilized can support relatively large directional antennas and can steer these antennas so they look in the direction of the Earth. Such directional antennas are a requirement for communication over interplanetary distances. These antennas must often fit into the aerodynamic shields needed for the initial phase of the trajectory through the Earth's atmosphere. Two main techniques have been devised for collapsible antennas that require relatively little space aboard the vehicle; these techniques use mechanical and inflatable devices. The mechanical devices depend upon springs, cables, or compressed gases to erect rigid structural members. In some cases they consist of special, heat-treated steel tape that can be extended and retracted by a drive mechanism. A simpler model is the inflatable antenna made of aluminum foil deposited on a plastic film base. Such antennas can be folded into small packages and erected by compressed gas.

Space Attenuation

The space attenuation L between an isotropic radiator which radiates power uniformly in all directions and an ideal receiving antenna of diameter D, at a distance R from the radiator, can be calculated as the ratio of the area of the parabolic antenna and the total area of a sphere of radius R. In symbols:

$$L = \frac{\pi D^2}{4} \Big/ 4 \pi R^2 = \frac{D^2}{16 R^2} \tag{4}$$

For practical parabolic antennas, with an efficiency of 0.5, the formula for the space loss becomes:

$$L = D^2/32R^2 \quad . \tag{5}$$

Note that the space attenuation between an isotropic radiator and a parabolic antenna is independent of the frequency.

In practice, equation (5) applies equally well for a half-wave dipole antenna, since the pattern of such an antenna is also independent of frequency and has an "average" gain of approximately zero decibels.

If the assumed isotropic radiator is replaced by a second parabolic antenna, the transmission loss caused by space attenuation between the two parabolic antennas will be decreased by the gain of the new reflector. This gain for a practical antenna has been given in equation (2). The total space loss between the two parabolic antennas can then be calculated from:

$$L = \frac{D_1^2}{32R^2} \cdot \frac{\pi^2 D_2^2}{2 \lambda^2} = \frac{\pi^2}{64} \cdot \frac{D_1^2 D_2^2 f^2}{R^2 c^2} \tag{6}$$

where D_1 and D_2 are the diameters of the two parabolical reflectors, f is the signal (carrier) frequency, and c is the velocity of light. Of course, for numerical computations, the units for the different quantities involved have to be consistent; i.e., if D_1 and D_2 are expressed in feet, then R must also be expressed in feet, f in Hertz, and c in feet per second. The loss is usually expressed in decibels, by simply making $L\ (db) = 10 \log_{10} L$.

Equations (5) and (6) are plotted in figure 2 for a 250 ft parabola on earth, and in figure 3 for a 90-ft parabola on earth. An isotropic radiator, as well as parabolic antennas of several different sizes, have been assumed at the space probe. These plots clearly show the advantage of using the highest practicable frequencies if the space vehicle has attitude stabilization and can properly orient its parabolic antenna to the ground station. The narrowness of the beam for high-gain antennas requires vehicle attitude stabilization and antenna orientation accurate to a few tenths or even hundredths of one degree.

Atmospheric and Ionospheric Absorption

Absorption losses in the troposphere are caused almost entirely by molecular absorption of oxygen and water vapor. For propagation paths between the earth and outer space the total absorption decreases sharply with the increasing elevation angle, because of the decrease of the path length through the atmosphere. The one-way tropospheric absorption curves are shown in figure 4, taken from reference 5. Note that below 15 gigahertz the loss curve is smooth and essentially constant, but resonance effects are noticeable at higher frequencies. The absorption peaks at 22.4 and 60 gigahertz are caused by water vapor and oxygen molecular resonance, respectively. Not shown on figure 4 is another strong, water vapor absorption line that occurs at 180 gigahertz [26]. The attenuation caused by these lines is variable with the atmospheric water vapor content; at any rate, the tropospheric loss, particularly at high elevation angles, can usually be neglected for the range of frequencies most commonly used in space communication systems, i.e., approximately for frequencies between approximately 100 and 5 gigahertz.

At microwave frequencies, rain attenuation in the transmission path can increase the path attenuation hence cutting down the signal-to-noise margin or even completely eliminating signal reception. Except under cloudburst conditions, the rain attenuation is less than one decibel per mile for frequencies below one gigahertz [27].

The absorption losses in the ionosphere are caused by the transfer of energy from the propagating electromagnetic wave to the electrons of the ionosphere layers. These losses are significiant only at frequencies slightly above the critical frequency, and in general can be neglected, as can be seen in figure 5, taken from reference 2.

Observations of the ionosphere have shown that the critical frequency exhibits diurnal, seasonal, and sporadic variations, oscillating between limits of 5 and 80 megahertz. Consequently, a lowest usable frequency of about 80 megahertz is specified for space communication systems designed to operate with high reliability.

Another effect, which is the result of the combined presence of the ionosphere and the earth's magnetic field, is the Faraday effect, i.e., the rotation of the plane of polarization of a plane-polarized wave. Upon entering

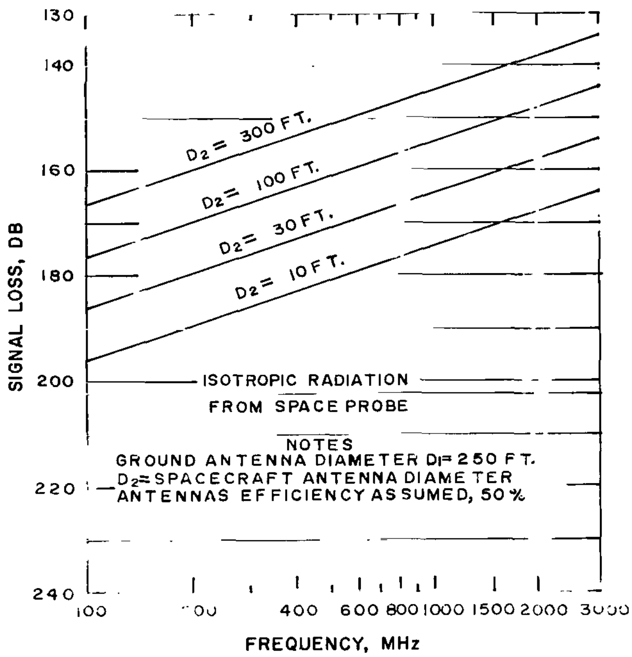

FIGURE 2. SIGNAL LOSS VERSUS FREQUENCY D_1 = 250 FEET AT 10^8 NAUTICAL MILES (PARABOLIC ANTENNAS)

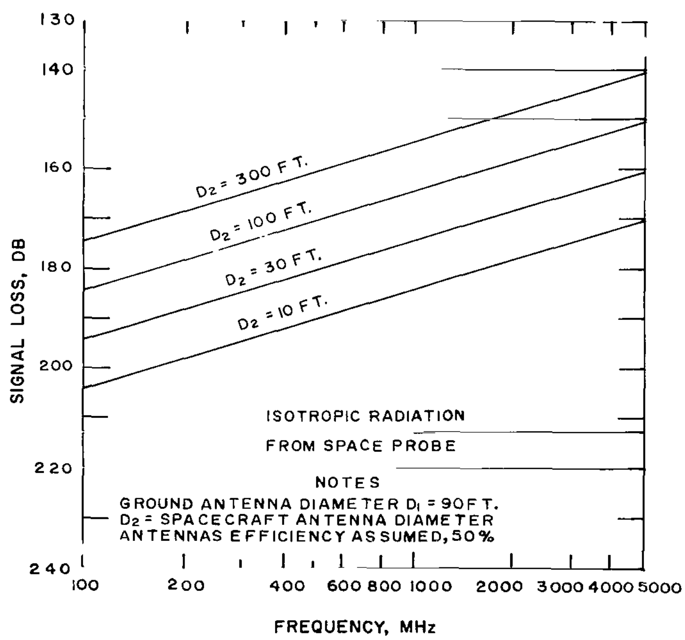

FIGURE 3. SIGNAL LOSS VERSUS FREQUENCY D_1 = 90 FEET AT 10^8 NAUTICAL MILES (PARABOLIC ANTENNAS)

the ionosphere, the incident plane-polarized wave is split into two circularly polarized waves, equal in amplitude, and rotating in opposite senses as they

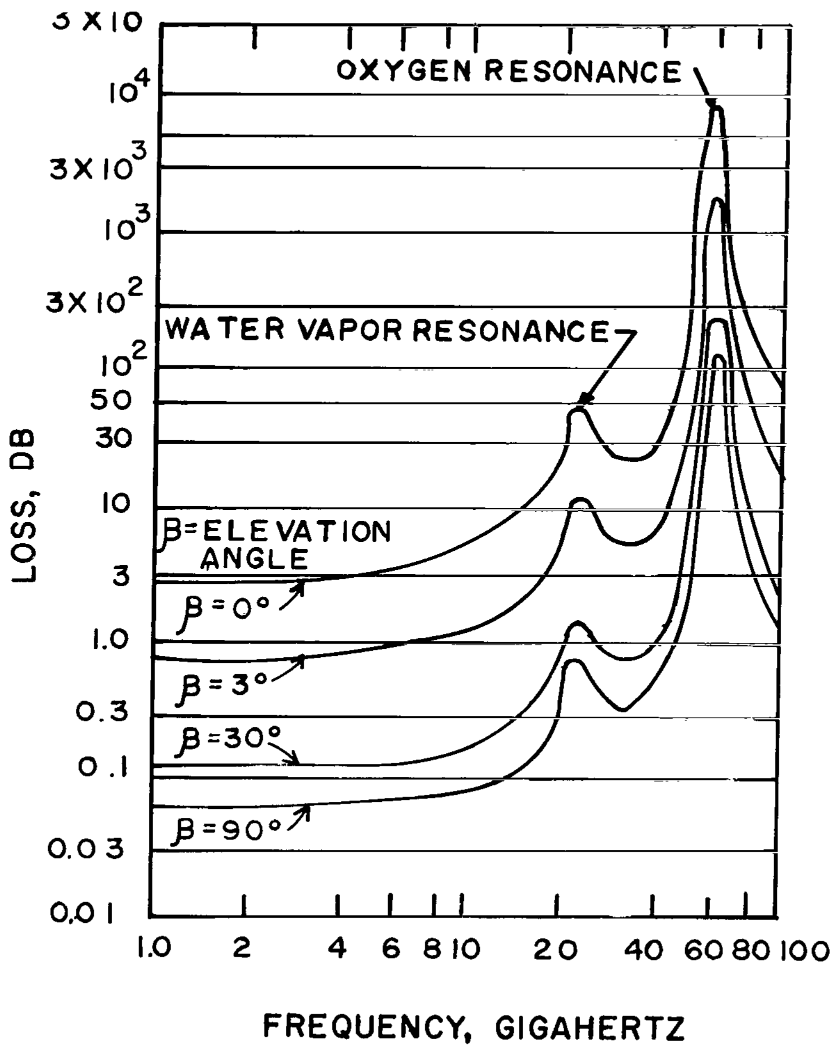

FIGURE 4. TOTAL ONE-WAY TROPOSPHERIC ABSORPTION

travel through the ionized region. These refracted components of the original wave travel through the charged layer at different velocities, and hence they emerge separated by some relative phase angle. This relative phase shift is equivalent to a rotation of the plane-polarized wave.

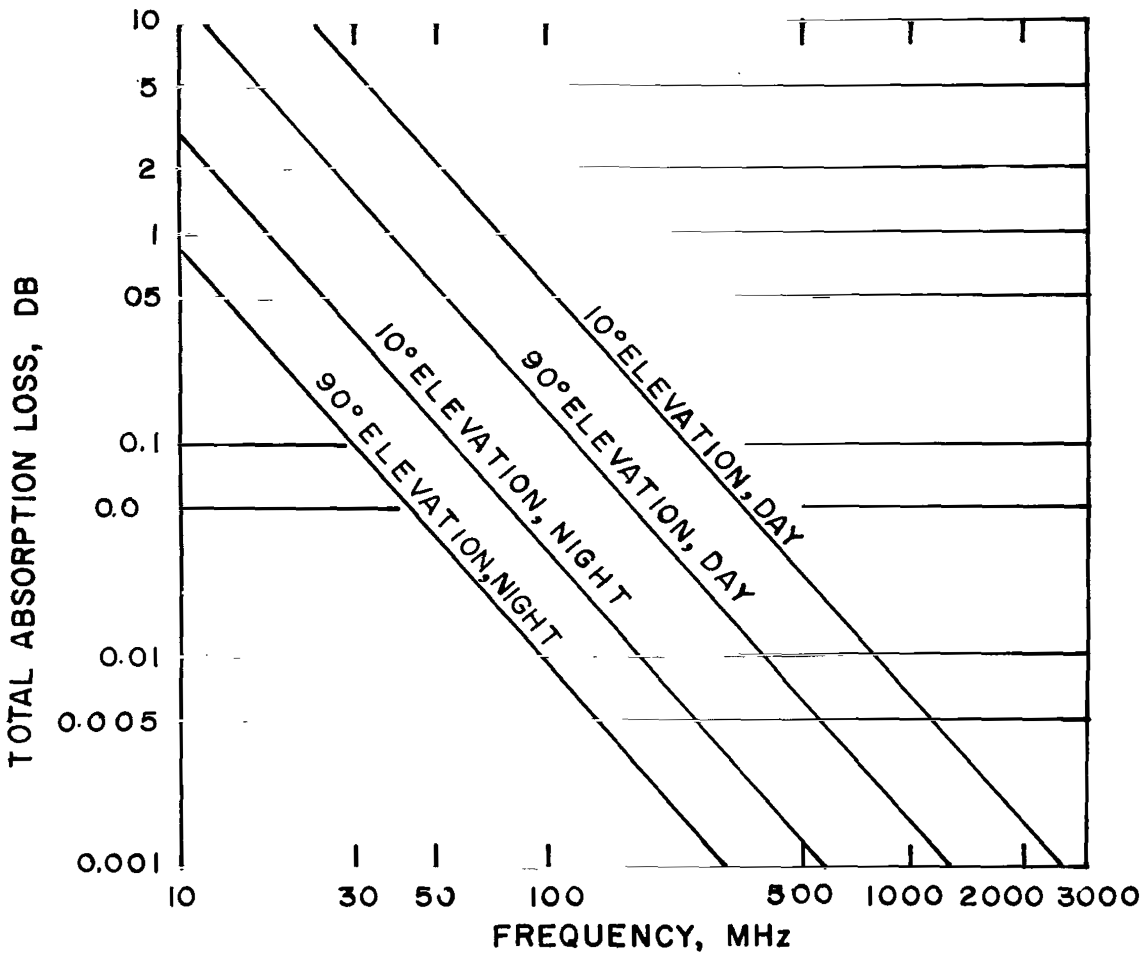

FIGURE 5. ONE-WAY IONOSPHERIC ABSORPTION FOR SOURCE AT A HEIGHT OF 1000 KM.

The result of the Faraday effect on a system using linearly polarized antennas is a decoupling of the transmitter and receiver, which manifests itself as an apparent power loss. This loss is negligible for frequencies above 1.4 gigahertz (less than three decibels), but may amount to several decibels at lower frequencies and low elevation angles. Since the ionosphere electron density varies with time in a complex way, to avoid serious Faraday fading over a wide range of frequencies, circular polarization, diversity reception, or some other techniques are indicated for earth-to-space communication systems [26].

Thus, we find that the earth's atmosphere is nearly transparent to the propagation of all frequencies between 80 and 15,000 megahertz. The upper limit of this atmospheric window is caused by molecular absorption by water vapor and oxygen in the troposphere, while the lower limit is caused by the opacity of the ionosphere. Tropospheric and ionospheric losses in this 80 to 15,000 megahertz frequency range are generally negligible, particularly at high elevation angles. Between these limits in frequency, the sensitivity of a conventional communication system depends primarily on cosmic and solar noise and internal receiver noise. For extremely low-noise systems using masers, parametric amplifiers, and similar devices, the sensitivity is primarily dependent upon resistive circuit losses, ground reflections, and thermal reradiations from the troposphere. These factors are described further in section V of this report.

Polarization

In a space communication system, the polarization problem is complicated by the fact that polarization changes constantly with the relative aspect and orientation of the space vehicle antenna with respect to the ground station, and also because of the Faraday effect. The effects of polarization, particularly in the lower portion of the useful frequency range, are loss of power and unreliability of the system.

In some cases, a partial solution is obtained (at the expense of three decibels in average transmission loss) by using linear polarization at one end and circular polarization at the other end of the radio link. In the case of an oriented, active earth satellite, polarization variations caused by satellite position may be accounted for by using circular polarization of the appropriate sense at both ends of the communication link [1].

The Faraday effect on a linearly polarized wave causes a rotation of the plane of polarization of only a few degrees at 1400 megahertz, the amount of rotation being inversely proportional to the square of the frequency. Consequently, at microwave frequencies the ionospheric effects on polarization are very small, and the polarization can be predicted or computed from the system geometry. At frequencies below 1400 megahertz, the Faraday effect is much larger and somewhat less predictable, but the solution to the problem is essentially along the same lines already described [26].

Interference

Interference is present in every communication system and greatly reduces the usable communications range. Interference affects the space communication system in several places: in the transmitter, where it affects the stability and clarity of the carrier signal by causing spurious signals; in the transmitter-receiver space link, where the effects depend on interference intensity, direction of arrival, and frequency spectrum characteristics; in the input circuitry of the receiver, where random motion of the electrons generates noise power dependent upon the temperature of the circuitry and the amplifier bandwidth; and in the receiver local rf signal-generating circuitry, where its effects are similar to the perturbations in the transmitter.

The most important of these possible sources are interference entering on the link and interference generated in the receiver input circuitry (noise power). External interference may be minimized by careful design of antennas. An antenna for example can almost cancel a point source interference by pointing a null pattern in the appropriate direction, by choice of frequency, and by appropriate coding of the transmission to make the signal distinctive. For large fixed installations, another important consideration is the choice of an isolated site as free as possible from man-made interference sources.

Internal interference sources (receiver noise power), and their effects on space communication systems, are discussed in section V of this report.

Doppler Effect

The frequency shift created by the Doppler effect is an important factor in the design of space communication systems. If f_o is the carrier frequency of a source moving at velocity v directly away from the receiver, the received signal will have a frequency f_d given by:

$$f_d = f_o \sqrt{\frac{1-\beta}{1+\beta}} = f_o \frac{\sqrt{1-\beta^2}}{1+\beta} \tag{7}$$

where $\beta = \frac{v}{c}$, and c = velocity of light.

For a vehicle moving directly toward the receiver:

$$f_d = f_o \sqrt{\frac{1+\beta}{1-\beta}} = f_o \frac{\sqrt{1-\beta^2}}{1-\beta} \tag{8}$$

Assuming a vehicle speed of 18.6 miles/second, we obtain $\beta = 10^{-4}$.

If f_o = 2000 MHz, the Doppler shift is approximately:

$$f_d - f_o \cong \mp \beta f_o = \mp 2 \times 10^5 \ H_z = \mp 200\text{kHz}$$

The minus sign in the result of equation (8) is for a vehicle directly receding from the receiver, and the plus sign for a vehicle directly approaching the receiver.

In space missions the relative velocity is a function of time, and the receiver can be tuned to allow for the Doppler frequency shift. Once a signal has been acquired, automatic tuning can adjust for changes in Doppler frequency. The Doppler frequency shift is of course useful for satellite orbital analysis and for space navigation. Doppler effects at relativistic velocities are extremely large; a brief analysis of their effects in relation to space communication in the distant future is contained in reference 5.

SECTION V. SIGNAL DETECTION ASPECTS

The useful sensitivity of a communication system is limited by its overall noise content. The various sources of noise that influence the operation of an Earth-to-space communication system can be divided into two groups: sources external or sources internal to the system. Under the assumption that man-made noise can be omitted (which is generally an acceptable assumption for a space communication system), the main external sources of noise are the Milky Way Galaxy, the Sun, the Moon, the other planets of our solar system, and the Earth's atmosphere. The main source of internal noise in the system is in the amplification stages of the receiver.

If the receiving antenna is pointed at a "black body" of temperature T degrees Kelvin, the noise P_n (watts) of radiation lying in the bandwidth (Hz), which the antenna receives, is given by the well-known expression

$$P_n = k\,T\,B \text{ watts,} \tag{9}$$

where $k = 1.38 \times 10^{-23}$ joules/ °K (Boltzmann's constant). To use this fundamental formula in the study of noise sources, it is a common practice to specify both external and internal sources of radio noise in terms of an equivalent temperature T_e, which would substitute for T in equation (9).

The equivalent noise temperature is a concept that originated in the field of radio astronomy and may be thought of as the noise power per unit of bandwidth. The equivalent temperature concept is not wholly true for a discrete source or even for distributed radio sources, because they do not behave exactly as black body radiators. It is, nevertheless, a useful and widely used concept in considering highly sensitive communication systems.

Noise

Cosmic and Solar Radio Noise. The ground receiving antenna of an Earth-to-space communication system, in addition to acquiring normal transmitter signals, acts as a radio telescope and picks up radiations from the Sun, the Milky Way Galaxy, the Moon, and other planets of the solar system, and perhaps from some "radio stars." The most important sources of noise for the purpose of this survey are the galaxy (the source of maximum cosmic noise) and the Sun (the source of maximum solar noise). Although many of the planets of our solar system and the so-called radio stars are well-known sources of radio noise [28], their influence can usually be ignored because of their very low energy level and because they are discrete or localized sources, affecting only specified directions in space.

The equivalent temperature of the cosmic noise received from various parts of the sky has been extensively investigated in radio-astronomy. A sketch summary of the data obtained is shown by the straight lines on the lower left side of figure 6, taken from Reference 1. The values of the "maximum" curve are obtained when the antenna is pointed at the galactic center (the center of the Milky Way); the "minimum" curve represents the background noise, or minimum galactic noise, which is completely independent of the direction of the receiving antenna, since the noise arrives from all directions [12]. From figure 6 it can be seen that for most space and interplanetary communication systems using frequencies in the gigahertz range, the cosmic noise temperature can be as low as 10°K; hence, it can probably be neglected, relative to other sources of noise like receiver noise and atmospheric thermal noise. For interplanetary communication systems operating below one gigahertz, the galactic noise would not be negligible; in fact, if the antenna were pointing at the galactic center, it would be one of the strongest noise sources. Some control over this pointing may be affected by appropriate choice of the spacecraft, of its trajectory, and of the time of year during which tracking and communication operations are performed.

The radio-frequency radiation from the Sun has a complex spectrum, but it is primarily composed of the thermal, or basic component, the slowly varying component, and bursts or flares of various types [27, 28]. The thermal component of the radio emission of the "quiet" (undisturbed) Sun, is always present and has a contiuous spectrum with completely random polarization. The origin of radio emission is thermal, and its frequency corresponds to temperatures at various levels in the corona and the chromosphere. The slowly varying component is most significant at decimeter wavelengths, and it also has a thermal origin. It changes slowly over several days with the rotation of the Sun, a change that is attributed to the "sunspots." The solar burst may have high noise intensity, but they generally are of very short duration, from tenths of a second to several minutes. They are produced mainly by rapid outward-moving disturbances in the Sun's chromosphere and corona. Occasionally, there is a type of burst with continuous emission in the centimeter through meter wavelength range that may last from several minutes to several hours. The origin of this type of burst has been attributed to synchrotron radiation [27].

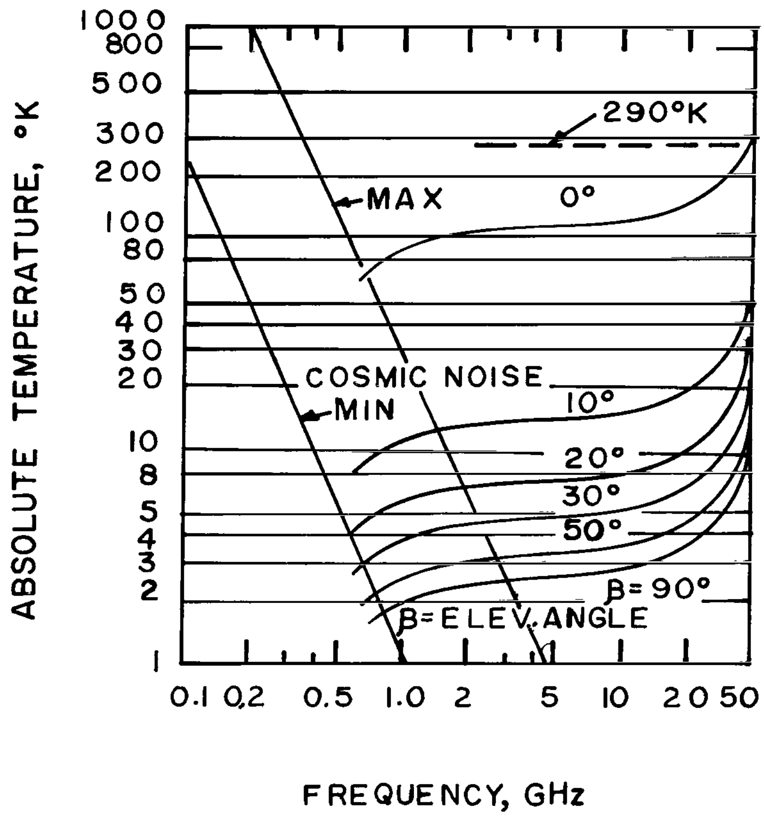

FIGURE 6. COSMIC NOISE TEMPERATURE AND ATMOSPHERIC NOISE TEMPERATURE

In general, in the absence of high sunspot activity and flares, above 20 megahertz the solar spectrum for the "quiet" sun is mainly composed of the thermal component enhanced by the slowly varying component, and, above 500 megahertz, it is composed only of the thermal component. Figure 7 taken from reference 28 is a simplified presentation of representative solar noise levels, with the 6000°K black body curve included for comparison. Because of the complexity of the solar spectrum, it is difficult to establish statistics as to the percentage of time the sun is disturbed for any given frequency. Hence, the "disturbed" sun curve represents only maximum probable values, not recorded maximums. In general, the observed noise level will lie between the "quiet" sun and "disturbed" sun curves shown.

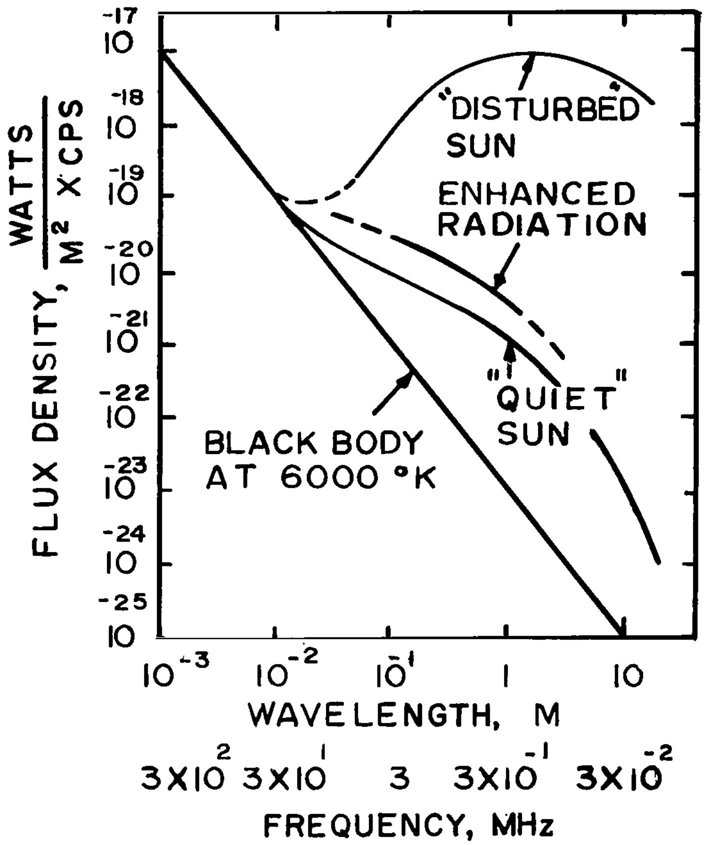

FIGURE 7. CHARACTERISTICS OF THE SOLAR NOISE RADIATION

The following example will illustrate how the choice of frequency can affect solar noise reception. If a receiving antenna with a very narrow beam-width is pointing directly at the Sun and the system is operating at a wavelength of one centimeter (f = 30,000 MHz), the antenna will receive noise correspond-ign to a temperature of 6000°K, the temperature of the Sun's photosphere. If the system were operating at a 3-m wavelength (f = 100 MHz), the noise received by the antenna would be much greater. Computations, based on the flux density at this wavelength, show that it would correspond to a much higher temperature, about 1,000,000°K (the temperature of the Sun's corona) under the assumption that quiet Sun condition existed. From the standpoint of noise reduction, the advantage of using the highest frequency compatible with the other requirements of the communication system is evident.

Atmospheric and Thermal Noise of the Earth. The transmitted microwave energy absorbed by the oxygen and water vapor molecules of the atmosphere is partly reradiated as thermal energy, so that some thermal noise is originated in the atmosphere surrounding the Earth. The energy noise level of these reradiations is very low and is negligible for most systems, but it does affect maximum-range systems which use extremely low-noise equipment. The curves of figure 6 show the effective temperature of this radiation for elevation angles (B) of 0°, 10°, 20°, 30°, 50° and 90° above the horizon.

Besides the atmosphere, the surface of the Earth, whose ambient temperature is about 290°K, also radiates radio noise. This radiation may enter the communication system through the side lobes of the ground antenna, but with well-built and appropriately placed parabolic antennas whose main beam is directed away from the Earth, the side lobe response will result in a noise temperature component of only 20-50°K [2]. Note that for planetary or spacecraft reception of signals from the Earth, the thermal radiation from the Earth would be represented by an effective temperature of about 290°K, which is the minimum noise temperature that the spacecraft antenna would encounter when pointed at the Earth. Another source of thermal noise generally of less importance is reradiation of absorbed energy by the ionosphere.

The noise contributions external to the space communication system are summarized in figure 8, reprinted from reference 2. The curves are plots of the total noise seen by an antenna at elevation angles of 10° and 90° as a function of frequency. The curves include minimum cosmic noise, atmospheric absorption effects, and Earth thermal radiation into the antenna back and side lobes. The values shown in the figure are optimal and can be greatly exceeded if the space probe antenna points toward the Sun, a bright radio star, or the galactic center. Space probe trajectories are therefore shaped to avoid these objects in the sky.

Receiver Noise. The noise power in watts generated within a receiver is determined by:

$$P_n = kTB(NF) \tag{10}$$

where $k = 1.38 \times 10^{-23}$ joules/°K; T = absolute temperature degrees K; B = receiver bandwidth in Hz; and NF = noise figure of the receiver (a dimensionless factor).

This formula is an extension of equation (9). The noise figure is a factor which compares the actual receiver noise level with the purely thermal noise level kTB, and is dependent upon the design of the front-end stage of the receiver. The concept of noise figure is very useful in conventional circuitry, where the sensitivity limitation is basically determined by resistance noise at room temperature. But it is misleading in space communication, because input circuit resistance noise at "antenna temperature" and cosmic and

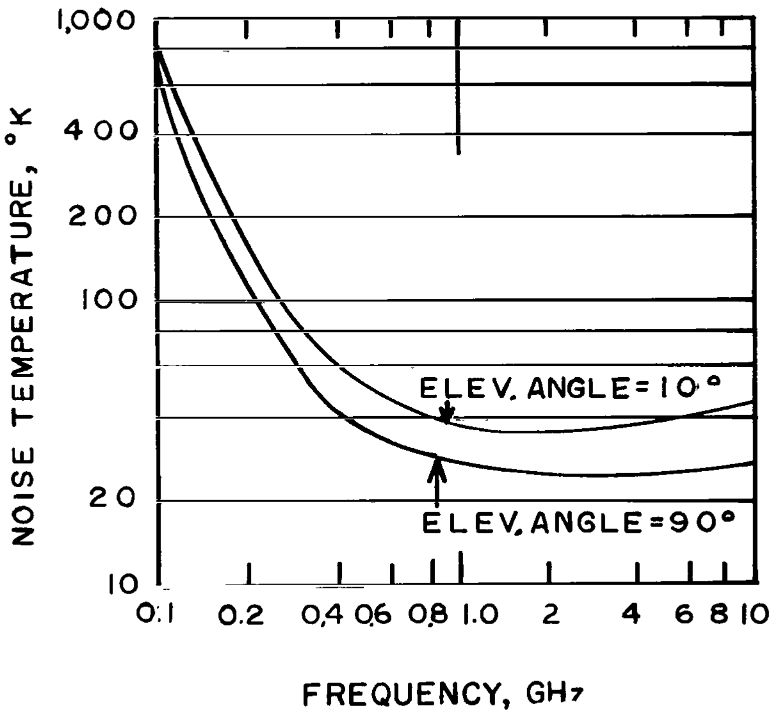

FIGURE 8. TOTAL EXTERNAL NOISE TEMPERATURE FOR LOSSLESS PARABOLIC ANTENNAS

atmospheric noises are usually far below room temperature. Consequently, a more suitable way of defining receiver sensitivity for systems using masers and other low-noise devices is by the effective noise temperature of the receiver. The effective noise temperature, T_r, is related to the noise figure, NF, of the receiver by the formula

$$T_r = 290\,(10^{NF/10} - 1) \tag{11}$$

where NF is measured in decibels.

As in conventional circuitry, the effective noise temperature of the receiver is also primarily determined by the design of its front-end stages. For two stages in cascade, the contribution of each stage to the overall noise temperature is

$$T_r = T_{r_1} + \frac{T_{r_2}}{G_1} \tag{12}$$

where T_r = overall effective noise temperature; T_{r1} = effective noise temperature of first stage; T_{r2} = effective noise temperature of second stage; and G_1 = gain of first stage. The effective noise power generated within the receiver is then:

$$P_n = k T_r B \text{ (watts)}. \tag{13}$$

Until recently, the noise generated in the initial stages of the receiver by electron tubes, transistors, and crystal mixers was the most important source of noise in communication systems operating at frequencies above 300 megahertz. But in the last few years, the successful development of extreme low-noise devices, such as parametric amplifiers, cooled crystal mixers, and masers cooled by liquid helium, have drastically reduced the receiver noise, thereby improving the signal-to-noise ratio.

Table 1, adapted from reference 1, shows some effective noise temperatures which are characteristic of very good receivers operating in the microwave range.

TABLE 1. EFFECTIVE NOISE TEMPERATURES OF MICROWAVE RECEIVERS

Type of Receiver	λ	Noise Temperature, °K	Noise Fig. db
Crystal mixer	1 cm	10,000	15.5
Crystal mixer	5 cm	1,500	7.9
Traveling-wave tube	5 cm	750	5.5
Parametric amplifier	5 cm	100	1.27
Maser	5 cm	10	0.16
Maser, expected future value	5 cm	3	0.04

It has been reported [29, 30] that noise figures have been achieved as low as 0.3 decibels (24°K) for a complete maser system and 0.2 decibels (15°K) for a traveling-wave tube system. Because the equipment must be cooled, maser systems are still rather bulky and heavy, but an effort is being made to develop packaged maser systems capable of long unattended operation, as required in a space probe communication system.

In conclusion, it is feasible to design a ground receiver system with effective noise temperatures of less that 30°K over the frequency spectrum from uhf through microwaves. Space probe receivers can now be built with noise temperatures of about 300°K, with substantial improvement expected in the near future. The net result of these drastic reductions in receiver noise will be that the factors which limit the sensitivity of a space communication system will no longer be receiver noise but external noise (cosmic, solar, and atmospheric thermal noise) and antenna noise, thermally generated in the resistive component of the antenna impedance.

A recapitulation of the noise sources that limit the operation of an Earth-to-space communication system, with the noise temperature of some typical devices, are shown as a function of frequency in figure 9 taken from reference 25. The curves shown for the expected noise temperature in 1970 of crystal mixers, masers, and parametric devices are perhaps pessimistic, in view of improvements made in those devices since the date of publication of the original article (December 1960).

Receiving Systems

The receiving systems for communicating with space probes, both at the ground station and in the space probe, should be able to detect extremely weak signals having Doppler shifts corresponding to range rates of 40,000 Hertz or higher. This frequency shift requires the use of a receiver with a wide tuning range. Since the power requirement and the interfering noise are directly proportional to the bandwidth, an optimum receiver should have a very narrow bandwidth and a wide tuning range in order to satisfy these simultaneous requirements. Even during periods when communication is of short duration, the range rate varies because of the rotation of the Earth, and automatic tuning of the receiver is generally necessary for an Earth-to-space communication system.

For signal reception, the most widely used receivers are of the phase-lock type, patterned after the phase-lock receivers of the Microlock system, developed by the Jet Propulsion Laboratory for the Pioneer series of lunar missions. The original Microlock system used a phase-locked receiver to achieve a lock-on sensitivity of -150 dbm with a 10 Hertz locked-loop bandwidth [11]. Receivers of this type now being used have reduced the bandwidth below 10 Hertz, and have simultaneously achieved higher sensitivities, detecting and locking on to carrier signals at a receiver power of -160 dbm or less. An additional advantage of these receivers is that they can achieve coherent detection of phase-modulated or frequency-modulated signals, provided the peak phase modulation does not exceed 90 electrical degrees, or about 1.6 radians. An example of an extremely sensitive system is provided by the JPL Venus Radar Experiment of early 1961. The system

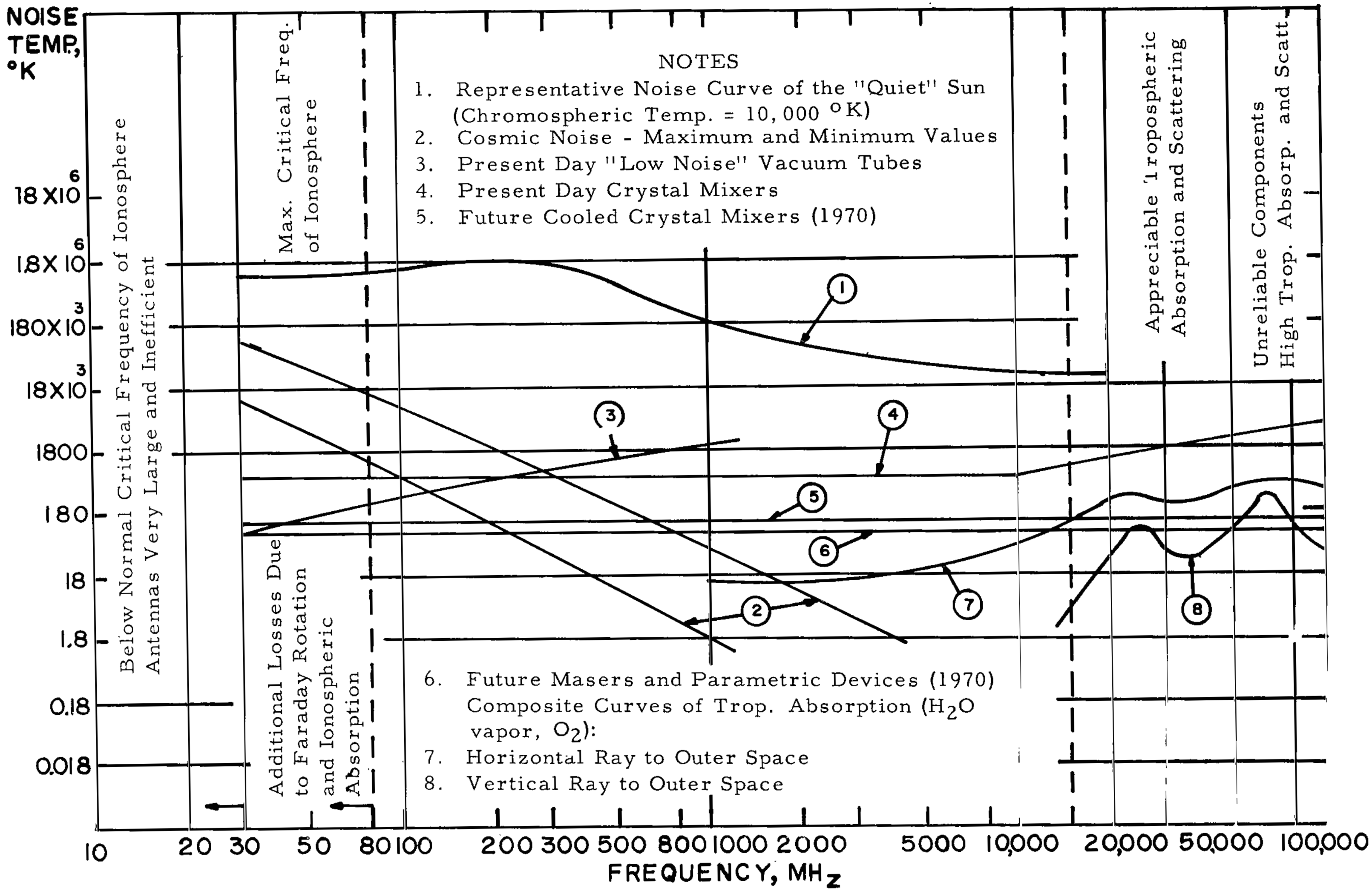

FIGURE 9. INTERNAL AND EXTERNAL SYSTEM NOISE SPECTRA

utilized both open-loop and closed-loop receivers of the radio-frequency phase-lock type, operating at a frequency of 2388 ± 0.2 megahertz. The sensitivity obtained with the receiving system in its normal operating mode (closed loop, 25 Hertz predetection bandwidth and 68-second integration time) was -181 dbm. This system, for example, is capable of detecting a 50-mW omnidirectional transmitter located on the surface of Venus, approximately 30 million miles from Earth [31].

SECTION VI. SOME THEORETICAL CONSIDERATIONS

This section presents a brief summary of those aspects of primarily theoretical or fundamental nature that are of considerable importance in space communication systems.

Information Theory

Information theory, also called communication theory, provides a mathematical framework for the quantitative study of communication systems. Communication theory states the problem of communication in a general way and arrives at certain possibilities and limitations that apply to any communication system. It provides an overall view or philosophy of communication in quantitative terms and enables us to distinguish what is possible and what is not possible to achieve in the system.

It is not the purpose of this section to give a summary of information theory, since the subject has been extensively treated in the literature [32, 33, 34, 35]. It will suffice to recall the concept of channel capacity as established by Shannon in his classic paper [32]. The channel capacity C (in bits per second), of a communication channel with bandwidth B (Hz) perturbed by white (gaussian) noise, is given by the expression.

$$C = B \log_2 \left(1 + \frac{P}{N}\right) \tag{14}$$

where P = average signal power and N = average noise power. The channel capacity establishes the theoretical maximum rate at which information can be transmitted through the channel (perturbed by gaussian noise) with an error rate approaching zero.

It is clear from equation (14) that for a given channel capacity, power can be exchanged for bandwidth very easily. Since power in most space communication systems is relatively expensive and bandwidth is not, the best possible use is made of bandwidth to save on the power required. To see the limit in power reduction that can be attained by increasing the bandwidth, we first substitute P_n (equation 9) for N in equation (14):

$$C = B \log_2 \left(1 + \frac{P}{kTB}\right) \quad . \tag{15}$$

The limiting value in the required power is obtained when the signal-to-noise ratio P/ kTB is very small compared to unity. Under these conditions the channel capacity becomes:

$$C = B \log_e \left(1 + \frac{P}{kTB}\right) \log_2 e = 1.44 \frac{P}{kT} \quad . \tag{16}$$

In another form this expression can be written:

$$P = 0.693 \text{ kTC} \quad . \tag{17}$$

This result indicates that even when we use a large bandwidth, i.e., $\frac{P}{kTB}$ is less than one, each bit of information that is transmitted through the channel will require a minimum energy given by:

$$P = \frac{P}{C} = 0.693 \text{ kT } \frac{\text{watts}}{\text{bit/sec}} = 0.956 \times 10^{-23} \text{T } \frac{\text{joules}}{\text{bit}} \quad . \tag{18}$$

This result (eq. 18) holds true only for ideal encoding, in which many characters representing many bits of information are encoded together into larger and larger blocks of data. In addition, the energy, P, that must be received per bit of information is proportional to the effective noise temperature, T, in the communication channel. Equation (18) clearly shows the basic reason why improvements in space communication systems are strongly dependent upon lowering the effective noise temperature in the systems.

Practical communication systems require much more energy per bit than the theoretical minimum because:

The Modulation System is Inefficient. The modulation system does not make efficient use of bandwidth in reducing the power required in the system.

The Signal Form is Inefficient. The signal in its original form does not make efficient use of the channel provided. For example, the characteristics of the signal and of the channel are not well matched.

The Signal Information Content is Inappropriate for Transmission. The information content of the signal is not commensurate with its characteristics; many signals contain a great deal of unneeded detail, or are greatly redundant. Although redundancy may be useful in that it may improve the reliability of the message, it is not usually present in its most efficient form.

A brief review of some of the schemes and methods used to increase the information efficiency of a message or of a channel is now in order. Various methods of modulation and signal characterization (encoding) which are of interest in space communication problems will be considered in following sections.

Modulation Systems and Encoding

A most important step in the design of communication systems is the selection of the type of modulation to be used in the system. Modulation can be defined as the process whereby a message is transformed from its original form into a signal that is more suitable for transmission and processing, to meet needs imposed by specific circumstances [36].

In this portion of the report, modulation theory will not be summarized, but the most significant modulation concepts and the results of various modulation methods, as applied in space communication systems, will be illustrated. Bibliographical references for modulation theory and modulation systems are quite extensive; interested readers will find a thorough and concise treatment of the subject as applied to space vehicle telemetry in references 36 and 37. A less complete paper is reference 38. A recent specific technique (PFM) is discussed in reference 39, while reference 40 considers modulation techniques in the ultraviolet and infrared regions of the spectrum.

The information which the space vehicle obtains, usually in the form of electric signals originating at measuring instruments, sensors, transducers, etc., is used to modulate the carrier frequency. The frequency of the information may vary from essentially direct current for data such as thrust-chamber pressure, to several megahertz per second for television. To convey this information properly, the carrier frequency must be a number of times greater than the maximum modulating frequency. The combination of the carrier frequency and the information frequency results in an information channel having a bandwidth dependent upon the type of modulation used. The bandwidth requirements of standard communication systems for various types of information are shown in table 2 taken from reference 3.

TABLE 2. TRANSMISSION BANDWIDTH REQUIREMENTS OF STANDARD COMMUNICATION SYSTEMS

Type of Information	Bandwidth Hertz
Manual keying telegraphy	15
Automatic telegraphy	100
Facsimile picture transmission (8 x 10 in. picture, 100 lines/in., transmitted in 10 minutes)	1,500
Speech telephony	2,800
AM broadcast	5,000
FM broadcast	20,000
Standard television (525 lines, 30 frames/sec)	4,500,000

Various methods of modulation are used, and the choice depends upon the mission and the degree of complexity of the system. The properly encoded data are caused to modulate the carrier frequency by any one of these methods: amplitude modulation (AM), either ordinary double sideband, single sideband, or any of its derived forms; frequency modulation (FM); phase modulation (PM); pulse amplitude modulation (PAM); pulse duration modulation (PDM); pulse position modulation (PPM); or pulse code modulation (PCM). These and other modulation methods are discussed in references 35 and 41.

For space applications, power efficiency is generally a primary consideration because of weight and power supply limitations associated with the spacecraft. Since, at the present time, transmission bandwidth is less expensive for space application than transmitter power, a number of modulation techniques have been used, or proposed for use, because of their efficiency in gain of usable power at the expense of bandwidth. These techniques have been developed through modifications and/ or improvements of some of the modulation methods mentioned above. In a recent paper [18], a comparative study was made of the following six modulation techniques for application to a wideband, high-resolution, Moon-to-Earth TV link:

(a) Frequency modulation (FM)

(b) Frequency modulation with negative feedback receiver (FMFB)

(c) Single sideband amplitude modulation (SSAM)

(d) Pulse code modulation (PCM)

(e) Pulse code modulation with error correction

(f) "Digilock" code modulation

The first three methods in this list are analog modulation methods, and the last three are digital methods. This particular example of a Moon-to-Earth TV link will provide an opportunity to establish a comparison of different modulation techniques and their relation to the saving of transmitter power.

The information that follows has been adapted from reference 18. For analog channels an average signal-to-noise ratio of 30 decibles will give a high quality TV picture more than 95 percent of the time. For digital systems, a binary-coded signal consisting of 5 information bits (32 levels of gray tones at the receiver), with a picture element error rate of 10^{-3} is assumed. Under normal viewing conditions, these specifications for analog and digital transmission techniques will result in approximately equivalent performance. A 600 x 600-line TV picture is assumed at a transmission rate of one frame per second. This rate requires a basic analog information bandwidth of 180 kilohertz, which leads to a premodulation signal bandwidth of 220 kilohertz, when allowance is made for additional bandwidth for synchronization and blanking. The signal bandwidth required for digital transmission depends upon the coding scheme adopted for conversion from analog to digital form.

The system parameters and the bandwidth requirements are listed in tables 3 and 4, respectively. The transmitter power requirement when analog transmission techniques are used is established by the design considerations outlined in table 5.

A threshold signal-to-noise ratio of six decibels is assigned to the receiver discriminator. The power required for digital transmission techniques is shown in table 6. For computational purposes, it has been assumed that the picture information and the synchronizing information are transmitted in digital form. The sampling rate is equal to twice the highest information frequency in the frame. Then, to transmit one 600 x 600-line TV frame per second, the information rate is 220, 000 x 2 or 440, 000 samples per second. In practice, a bandwidth of 1.5 times the information rate is adopted. Since a 5-bit code is assumed, this indicates a bandwidth of 3.3 megahertz for the PCM system.

TABLE 3. SYSTEM PARAMETERS FOR MOON-TO-EARTH TV LINK

Spacecraft Antenna Gain	28 db
Earth Antenna Gain	50 db
Ground Receiver System Noise Temperature	200°K
Transmitter Frequency	2,300 Mc
Range	2.5×10^5 miles
Geometric Resolution of TV Frame	600 x 600 lines
System Power Margin	6 db

TABLE 4. TRANSMISSION BANDWIDTH REQUIREMENTS AT ONE TV FRAME PER SECOND

Modulation System	Bandwidth, MHz
Frequency Modulation	2.35
Frequency Modulation with Feedback (FMFB)	4.40
Single Sideband Amplitude Modulation	0.22
Pulsecode Modulation	3.30
"Digilock" Coding	10.50
Error Corrected PCM	6.60

A study of the results shows that the FMFB system clearly requires the least amount of transmitter power; only 0.87 watts if idealized rectangular intermediate frequency filters and infinite feedback in the receiver are assumed (Table 5). Present state-of-the-art information indicates that a practical FMFB system would operate within a 2-dB loss from that of the ideal system, i.e., it would require about 1.4 watts. With regard to power, the next most competitive system employs "Digilock" coding and requires 4.6 watts of transmitter power. An ordinary FM system is almost as efficient as the "Digilock" system, requiring a transmitter power of 4.9 watts.

In references 1 and 42, it is shown that ordinary FM is at best about twenty times less efficient in the use of power than optimum channel capacity allows. An analysis performed in reference 42 indicates that a well-designed FMFB system can be expected to operate with only about four times the theoretical minimum power requirement given by information theory (it would require $4 \times 0.956 \times 10^{-28}$ T watts per bit per second). These results agree closely with those reported in reference 18. Note that an FMFB system requires a greater modulation index at the transmitter than an ordinary FM system. For equivalent performance, an FMFB system requires greater transmission bandwidth but less transmitter power than an ordinary FM system. Theory shows that for the same output signal-to-noise ratio and identical discriminator signal-to-noise thresholds, the ratio between the transmitter power required by the FM and FMFB systems is given by the following equation, where M is the modulation index associated with the FM system:

$$\frac{P(FM)}{P(FMFB)} = M + 1 \qquad (19)$$

The relatively low signal-to-noise threshold of 6 decibels for an FM system is achieved by using phase-locked or pulse-averaging discriminators. In an FMFB system, the feedback is applied to effectively reduce the apparent signal deviation in the intermediate frequency amplifier. The basic circuit for this technique is shown in figure 10, where the output of the discriminator (frequency detector) is fed back into the local voltage controlled oscillator (VCO) causing this oscillator to partially track the frequency-modulated input signal. The result of mixing the VCO signals with the incoming signals is an intermediate frequency signal with greatly reduced deviation. This reduction in intermediate frequency bandwidth results in a corresponding improvement in threshold performance and reduces the required transmitter power as shown in table 5. With a large feedback factor, the intermediate frequency bandwidth approaches the limiting value of twice the highest modulating frequency.

Finally, among the analog systems, single sideband modulation uses the smallest receiver bandwidth (equal to the transmission bandwidth), but also requires the largest transmitter power, since in this system there is no trade-off of bandwidth for power.

Among the digital modulation systems, which intrinsically have higher accuracy than analog systems, the most efficient one is the "Digilock" system, which requires 16/ 5 times as much bandwidth as ordinary PCM. The basic circuit for a PCM system is shown in figure 11.

In a binary PCM system, each sample of picture data is coded into a 5-bit information word. Efficient transmission is accomplished by employing

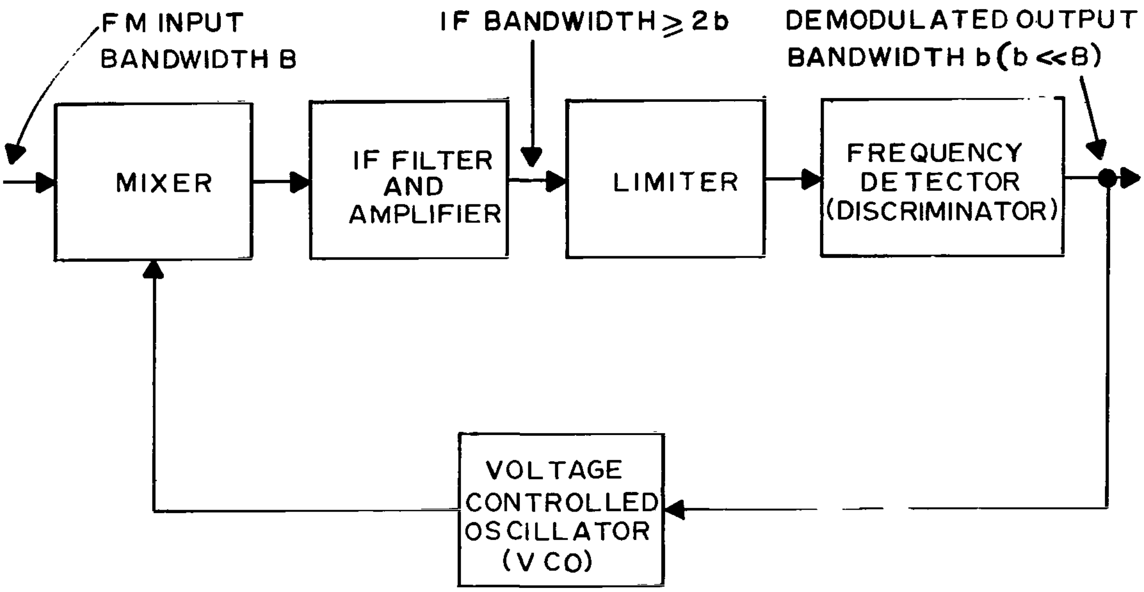

FIGURE 10. BASIC FREQUENCY MODULATION, NEGATIVE FEEDBACK RECEIVER

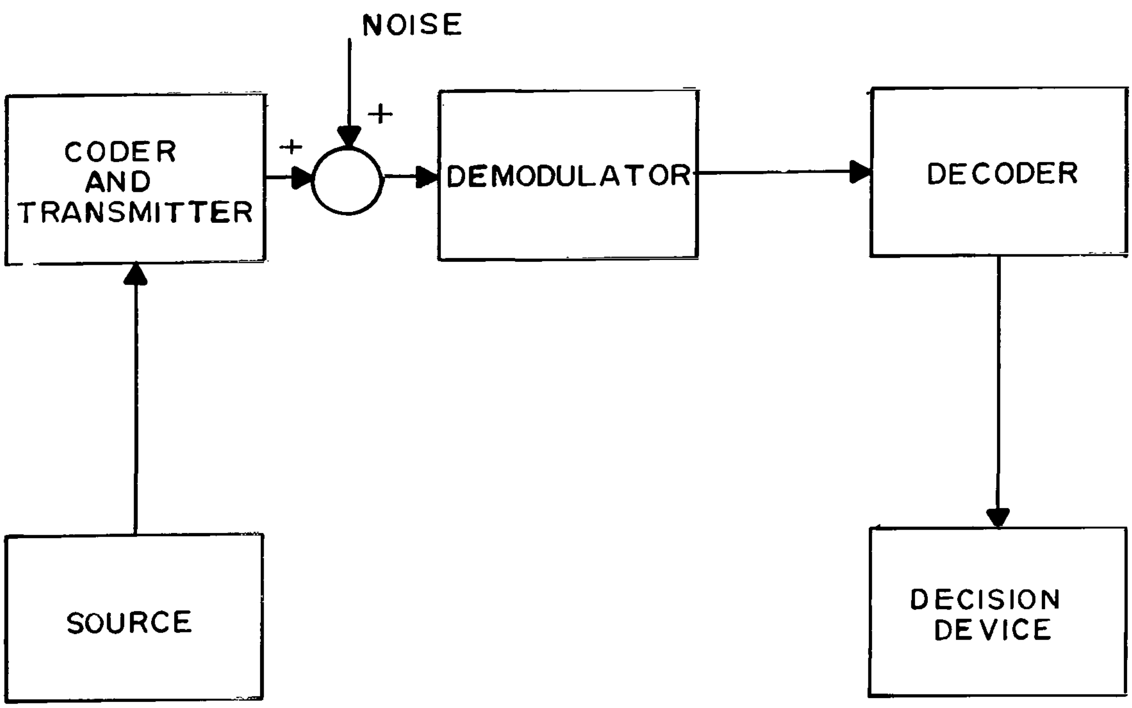

FIGURE 11. BASIC PULSE CODE MODULATION SYSTEM

TABLE 5. POWER REQUIRED FOR ANALOG SYSTEMS AT TRANSMISSION RATE OF ONE TV FRAME PER SECOND

System Parameters		Frequency Modulation	Frequency Modulation with Feedback Receiver	Single Sideband Modulation
Spacecraft Antenna Gain	28 db			
Earth Antenna Gain	50 db			
Moon-to-Earth Path Loss at 2300 Mc	-211.7 db			
Polarization Loss	- 3 db			
Net Path Loss	-136.7 db			
Receiver Noise Density Per Unit Bandwidth at 200° K	-205.6 db/Hz			
Receiver Bandwidth at 1 Frame/Sec		2.35 Mc	4.44 Mc	0.22 Mc
Receiver Noise Power		-141.8 db	-149.2 db	-152.2 db
Discriminator Signal-to-Noise Ratio Threshold		6 db	6 db	--
FM Modulation Index for Signal-to-Noise Ratio = 30 db		M=4.3	M=9	--
Required Receiver Power		-135.8 db	-143.2 db	-122.2 db
Net Path Loss		-136.7 db	-136.7 db	-136.7 db
Required Power (Theoretical)		+ 0.9 db	- 6.5 db	+ 14.5 db
Transmitter Power with 6 db System Margin		4.9 w	0.87 w	112 w

pulse-to-pulse carrier phase-shift keying at the transmitter and a differentially coherent detection process at the receiver, usually by means of matched filters [43, 44].

The "Digilock" system is an improved PCM system which makes use of orthogonal coding. Coded orthogonal sequences are defined as sequences coded such that the correlation between any two waveform sequences is always zero, except when the waveform is correlated with itself (autocorrelation), in which case the correlation coefficient is unity [33]. The 5-bit digital words, corresponding to 32 discrete levels of the sampled data, are represented for transmission purposes by 32 mutually orthogonal 16-bit binary codes of the Reed-Muller type and transmitted by phase modulation of the rf carrier [45]. The receiver consists of 32 correlation detectors, one for each binary-code word. The channel representing the transmitted message yields a large positive output at the end of a word period and the remaining channels yield no output, due to the orthogonality of the code. The decision device samples all the channel outputs at the end of a word period and selects the largest output as the sent message.

In the error-corrected PCM, in addition to the message pulses, extra pulses are transmitted to detect and correct possible message error by means of parity checks. Hence, at the price of more pulses, accuracy is improved for a given amount of signal power. One such code, the Hamming code 12, corrects single errors and detects double errors in a message block. For a 5-bit word this is achieved by using five extra pulses, four pulses to correct single errors and one pulse to detect double errors. Table 6 shows that the error-corrected PCM system requires slightly more power than ordinary PCM.

Error probabilities as a function of signal-to-noise ratio for various digital systems will not be dealt with in this report. Error probabilities are described in reference 44, which also presents an excellent discussion of correlation linear synchronous detection methods. A good general discussion of modern digital systems, including modulation and coding aspects, efficiency, and circuit and design considerations, is contained in reference 43. Another good study, particularly for telemetry systems, is reference 45. References 43 through 56 can be consulted for specific purposes in regard to space telemetry.

Although the comparison of these six modulation techniques has been made for their specific application to a TV link between Moon and Earth, the implications of the results are more general and can be extended to other types of sampled-data communication systems, such as telemetry data. The list of modulation systems considered is by no means an exhaustive one, but

TABLE 6. POWER REQUIRED FOR DIGITAL SYSTEMS AT TRANSMISSION RATE OF ONE TV FRAME PER SECOND

System Parameters		PCM	"Digilock"	PCM Error Correction
Ground Antenna Gain	50 db			
Spacecraft Antenna Gain	28 db			
Moon-to-Earth Path Loss at 2300 Mc	-211.7 db			
Polarization Loss	- 3.0 db			
Net Path Loss	-136.7 db			
Receiver Noise Density per Unit Bandwidth at 200°K	-205.6 db w/Hz			
Receiver Bandwidth (at 1 TV Frame/Sec)		3.3×10^6 Hz	10.5×10^6 Hz	6.6×10^6 Hz
Receiver Noise Power		-140.4 db w	-135.5 db w	-137.4 db w
Required Signal-to-Noise ratio		6.0 db	- 1.4 db	3.8 db
Demodulator Loss		0.8 db*	0.8 db	0.8 db
Required Receiver Power		-133.6 db w	-136.1 db w	-132.8 db w
Required Power (Theoretical)		3.1 db w	0.6 db w	3.9 db w
6 dB System Margin		9.1 db w	6.6 db w	9.9 db w
Transmitter Power		8.2 w	4.6 w	10.0 w

* In Practice about 1 dB greater demodulator loss should be expected for very low signal-to-noise ratio. However, for purpose of comparison, the same demodulator loss is assigned to all digital techniques.

it does indicate the types of efficient modulation methods applicable to space communication.

SECTION VII. SYSTEM PERFORMANCE IMPROVEMENTS

In the space communication systems previously discussed, it has been assumed that the spacecraft was provided with unity gain antennas. It has also been assumed that these systems depended upon solar cells for power, resulting in severely restricted transmitter power. In this section, a brief review will be made of those areas where progress which could lead to a sizable improvement in system capability and performance is likely to be achieved.

Spacecraft Directional Antennas

By using directional antennas on spacecraft, a substantial improvement in system performance can be obtained. For the next few years, the spacecraft antenna gain will likely be limited by the achievable size of the parabolic reflector. For a parabolic antenna of given size, the gain is inversely proportional to the square of the wavelength, or directly proportional to the square of the frequency, that is, $G = 1/2\ (\pi\ D/\lambda)^2$. From this standpoint, the advantage of using high frequencies is evident. For example, if a spacecraft antenna system having a gain of 33 decibels can be provided[1], the information bandwidth can be increased by a factor of 2000 for constant transmitter power at either end of the communication link, the transmitter power can be reduced by the same factor, or this gain in the communication system can be used in many other ways.

Spacecraft antennas of tens, or even hundreds, of feet in diameter may be feasible in the future; but large antennas pose additional serious technical and economic problems. First, the mechanical tolerances of a high-gain antenna are severe, because the antenna surface irregularities limit the coherence of the radiated (or collected) energy, a limitation that results in a degradation of the antenna gain. When the wavelength is reduced to the point that the irregularities are $\lambda/4$, there is a complete loss of the antenna gain. This "gain limiting" effect makes it fruitless to raise the operating frequency beyond the capabilities of the antenna. It should also be remembered that the "dish" surface has to maintain the required accuracy under varied conditions, such as varying attitudes, sun heat, etc. Second,

[1] A spacecraft antenna system having a gain of 33 decibels can be obtained at approximately $f = 2$ gigacycles with a "dish" of diameter, $D = 10$ ft.

because the beamwidth of an antenna is inversely proportional to the square root of the gain (eq. 3), the pointing accuracy for a high-gain antenna has to be within tenths of a degree or the communication link will fail. An example is the 33-dB gain antenna which should have a pointing accuracy of about 3.7 degrees. The pointing accuracy of a spacecraft antenna of even higher gains will require a very advanced attitude stabilization system. Third, the antenna surface irregularities and deflections tend to assume magnitudes proportional to the size of the antenna; hence, a maximum practical antenna size is achieved for a given operating wavelength. This problem can be somewhate mitigated by careful design and construction practices; but since the cost of high-gain antenna systems increases greatly when tight tolerances have to be maintained on the reflector surface, the cost becomes prohibitive when compared with the relative increase in performance.

It therefore appears that directional spacecraft antennas of moderate sizes with probable gains in the range from 10 to 35 decibels will be used in the near future.

Ground Antennas and Ground Stations

Much of what was said regarding spacecraft directional antennas is also applicable to the parabolic reflectors used at the ground stations. These antennas are usually steerable; so, in addition to possible surface irregularities caused by thermal stresses (sun heat conditions), there are mechanical stresses introduced by the steering operation, and wind-loading and other atmospheric phenomena.

The result of practical measurements on typical parabolic antenna systems indicates that there is a maximum gain factor ratio, D/λ, which is very difficult to exceed before serious gain degradation appears. Where θ is the magnitude of the surface irregularity and D is the antenna diameter, the limit in practical antenna size is frequently determined as a function of the factor D/λ and the fractional manufacturing tolerance, $t = \frac{\theta}{D}$. Figure 12, reproduced from reference 27, shows serious gain reduction for $\frac{D}{\lambda} > 100$ when $t = \frac{1}{2000}$, and for $\frac{D}{\lambda} > 200$ when $t = \frac{1}{4000}$. These results seem to confirm a practical rule given in reference 12, which indicates that the limiting value of the factor ratio $\frac{D}{\lambda}$ is about 300 to 400 for fully steerable antennas. Figure 12 shows also that up to about $\frac{D}{\lambda} = 70$, the gain curves for $t = 0$ and for $t = \frac{1}{2000}$ coincide. Thus a tolerance of $t = \frac{1}{2000}$ would introduce no

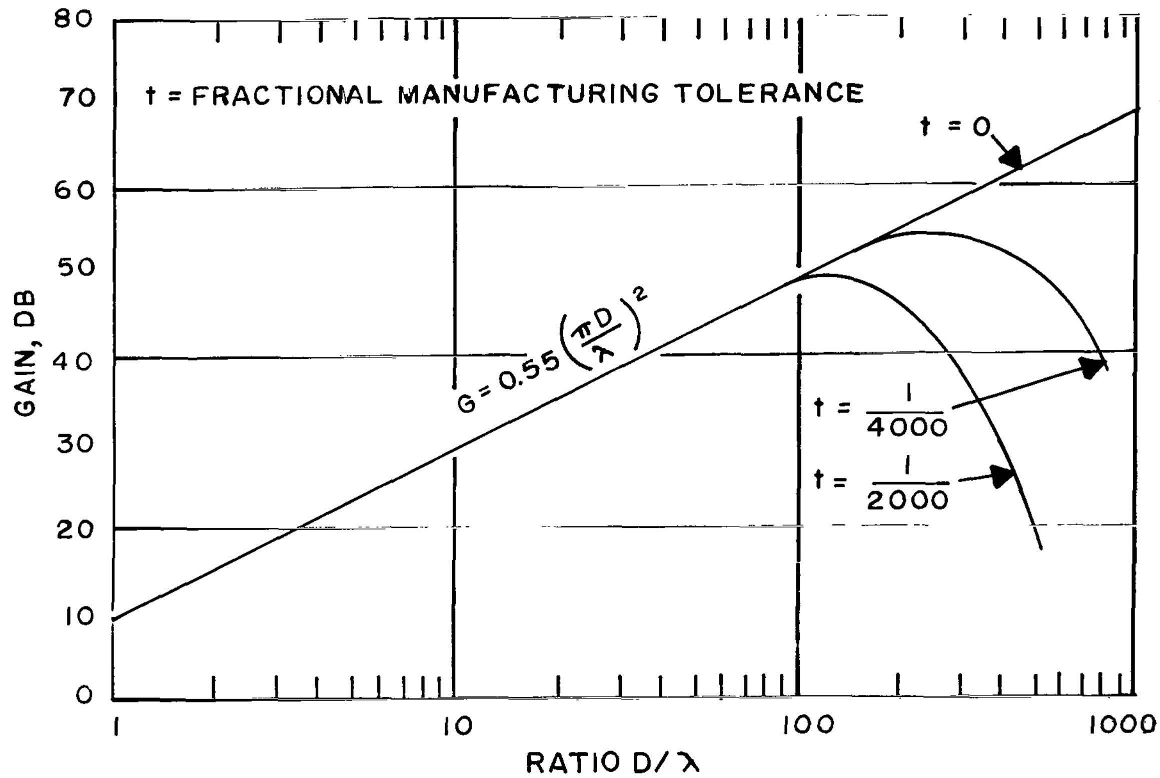

FIGURE 12. REDUCTION IN ANTENNA GAIN AS A FUNCTION OF TOLERANCES AND THE RATIO D/ λ

gain loss in the 85-ft Goldstone reflector when $\lambda > \frac{85 \text{ ft}}{70} = 1.21$ ft (f = 820 MHz). The respective value would be $\lambda > \frac{85 \text{ ft}}{200} = 0.425$ ft (f = 2.3 GHz) for a tolerance of $t = \frac{1}{4000}$.

Figure 12 also shows the practical antenna limit of useful gain in Earth-to-space communication systems to be about 67 to 70 decibels. A beamwidth of about one milliradian = 0.057°, which is approximately the value of the random refraction errors in the atmosphere, corresponds to the 67 to 70 decibels gain limit. Thus, the inhomogeneities in the troposphere cause the radio waves coming to or from a large aperture antenna to appear to be out of focus, setting an upper limit to practical, steerable, ground antenna sizes at about 300 feet diameter.

Large ground communication networks covering the entire surface of the Earth are required to track, read out information, and transmit commands to earth satellites and space probes. These networks feed their data to computing centers which determine the vehicle's orbit or trajectory, and reduce the data collected. The size of the ground tracking and communication network required depends upon the space vehicle's orbit trajectory parameters and upon the amount of communication required. Depending upon the mission being supported, the NASA networks can be placed in three categories: unmanned Earth satellite missions, deep space missions (lunar and planetary); and manned space exploration missions.

The ground network used for unmanned satellite missions is an outgrowth of the Minitrack system, created in 1957 for the Vanguard satellite. The network consists of 13 stations located throughout the world so that at least one station is within a satellite's line of sight during every orbit, regardless of the inclination or the orbital altitude. The system operates in the frequency band of 136 to 137 megahertz and requires some preacquisition information. Future satellites will require broader bandwidths compared with present requirements, and NASA is planning to use several 85-ft parabolic antennas and two high-frequency bands (400 to 401 megahertz and 1700 to 1710 megahertz) to meet these broader bandwidth requirements.

The data acquired by the ground network are processed at the Goddard Space Flight Center, Greenbelt, Maryland, which also supplies each station with operational control data and the necessary prediction information for spacecraft acquisition. The radio information is supplemented by optical information about the satellite's position, which is obtained by 12 optical tracking stations provided with special telescopic cameras.

The Deep Space Instrumentation Facility (DSIF) of NASA is used for tracking and data acquisition in lunar and planetary missions. There are three stations: Goldstone, California; Johannesburg, South Africa; and Woomera, Australia. They are geographically spaced about 120° in longitude and within latitudes 30° North and 30° South. This network allows coverage of any spacecraft going to the moon or planets from at least one station at all times. These "high sensitivity" stations use 85-ft steerable parabolic antennas and are located in isolated areas to avoid man-made interference and noise. Goldstone has two additional 85-ft steerable antennas, and its control center is at the Jet Propulsion Laboratory, Pasadena, California. The frequency presently used for earth-to-space transmission is 890 megahertz and is 960 megahertz from spacecraft to earth. Since 1963 the stations have operated in the 2110-2120 MHz band for earth-to-space, and 2290-2300 megahertz for spacecraft-to-Earth. A wideband detection capability, including video information, is planned for integration into the DSIF as part of the 2290-2300 MHz receiver [57, 58].

The ground-support requirements for manned space orbital missions are met by the NASA network initially implemented for Project Mercury. With some minor changes, this network is supporting Project Gemini. The complex instrumentation to support these orbital missions consists of equipment at some 18 stations located throughout the earth, including two ships, the control center at Cape Kennedy, and the computing and communications center at Goddard Space Flight Center, Maryland. Almost all stations have full capability to receive and transmit voice. The development of the Manned Space Flight Network (MSFN) to support the Apollo Mission is reported in reference 59.

Spacecraft Transmitter Power

Vacuum-type tubes (triodes and tetrodes) are used as final stages in the transmitter, in the maximum frequency range of approximately 2000 megahertz. At frequencies higher than 2000 megahertz, microwave-type tubes are used. The most common types of microwave tubes are traveling-wave tubes, reflex klystrons, and multicavity klystron amplifiers for high-powered transmitters. Approximate power levels that are available from these various types of tubes and their efficiencies are listed in reference 27.

Before discussing possible improvements in the spacecraft transmitter, it will be useful to find the power received, P_R, by an antenna of area A_R and efficiency η_R, at a distance R from a transmitter of power P_T and antenna gain $G_T = \eta_T \left(\frac{\pi D_T}{\lambda}\right)^2$, where η_T is the efficiency of the transmitter antenna. At a distance R from the transmitter, the power per unit area is $\frac{P_T G_T}{4\pi R^2}$. The power collected by the receiving antenna is then:

$$P_R = \frac{P_T}{4\pi R^2} \cdot \eta_T \cdot \frac{\pi^2 D_T^2}{\lambda^2} \cdot \eta_R A_R$$

$$= \frac{P_T}{\lambda^2} \cdot \frac{1}{R^2} \cdot \eta_T \cdot \frac{\pi D_T^2}{4} \cdot \eta_R A_R$$

$$= \frac{P_T}{\lambda^2} \cdot \frac{1}{R^2} \cdot \eta_T A_T \cdot \eta_R A_R \,. \qquad (20)$$

This expression indicates that for given antennas, it is $\frac{P_T}{\lambda^2}$, the ratio of the transmitter power to the square of the wavelength, which is important in determining the received power. This conclusion can be applied to the transmitter power considerations in space communication systems.

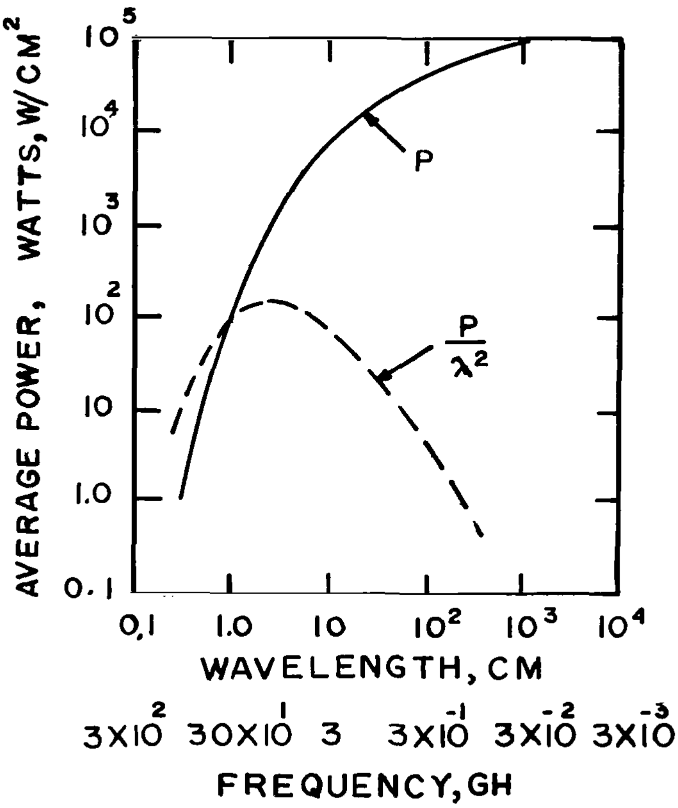

FIGURE 13. AVAILABILITY AND EFFECTIVENESS OF RADIO-FREQUENCY POWER AS A FUNCTION OF FREQUENCY

The solid line of figure 13, taken from reference 1, shows the power that can be obtained from various types of tubes as a function of wavelength. The dashed line has been obtained by dividing the solid curve by λ^2. It shows how effective the available power is at various wavelengths when used with a transmitting antenna of a given diameter. This dashed-line curve shows a maximum power output in the range between 1 and 10 centimeters (30 to 3 gigahertz), a result that also shows the advantage of using high frequencies for long range space communication.

The amount of radio-frequency power that can be generated at microwave frequencies can be increased by using parallel tubes or developing higher power tubes. At the present time, however, power supply and weight are the fundamental limitations of transmitter power in space vehicles, and improvements in the vehicle transmitter power are dependent upon the development of high-power electrical systems.

Many proposed schemes of power generation for the spacecraft needs of future space missions are discussed in reference 60. It is estimated that nonpropulsive power needs will increase about 1000 times in 10 years, from a requirement of less than 100 watts for early satellites to several hundred kilowatts forecast for satellites of the early 1970's. Figure 14, taken from reference 60, shows the anticipated nonpropulsive power requirements plotted against the

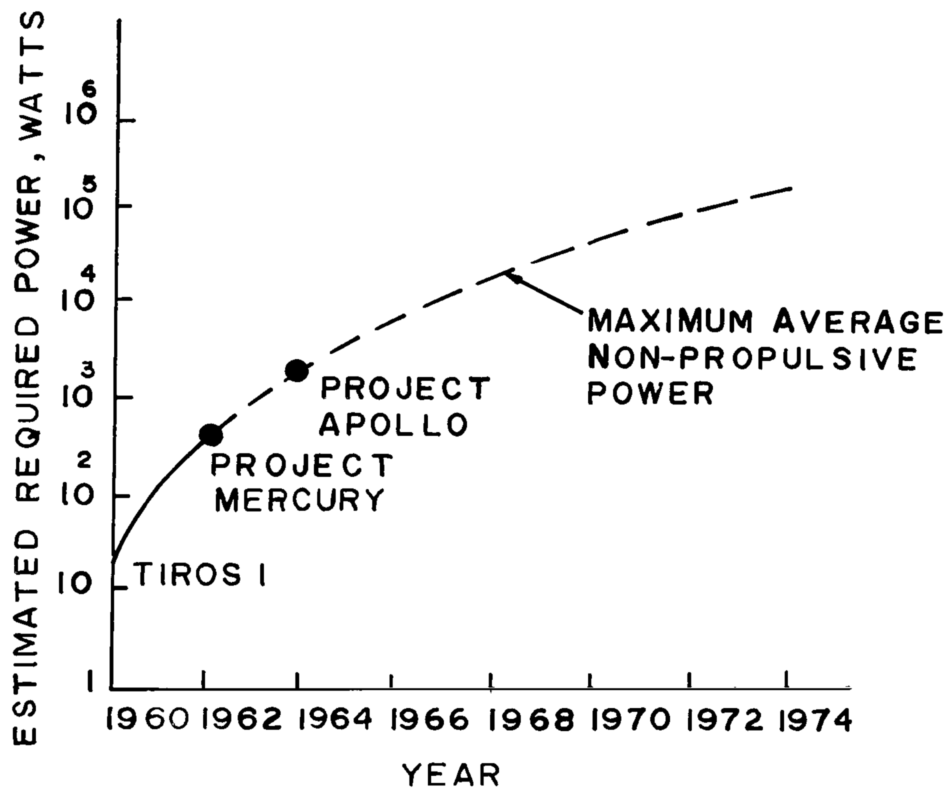

FIGURE 14. ANTICIPATED NONPROPULSIVE SPACE-POWER REQUIREMENTS

calendar year. For example, Project Apollo would require only a few kilowatts of power, while television signals from the planet Jupiter may require one megawatt of power. Power requirements for electrical propulsion may run into the tens of megawatts, but this subject is outside the scope of this report.

It will suffice in this report to indicate that the most promising sources of power being investigated are: thin-film solar cells, to obtain power up to one kilowatt or more; fuel cells, already selected as power systems for both the Gemini and Apollo missions; solar power systems, which are expected to provide as many as 30 kilowatts within a few years by employing large parabolic reflectors to focus heat from the sun on a mercury boiler "Sunflower" system, or use it in thermionic conversion devices; and nuclear reactor systems from a few kilowatts to megawatts.

The effective power required by the spacecraft transmitter depends on the over-all efficiency of the conversion into radio-frequency power. Over-all efficiencies between 20 and 30 percent can be achieved with the present state-of-the-art; thus, if a certain future space mission requires a 30 kw transmitter, the primary power source should provide between 100 and 150 kilowatts. This requirement is well within the capabilities of the most advanced power sources that are now being investigated.

Such large-power transmitters, with directional antennas, will permit a substantial increase in information bandwidth, information rate, maximum communication range, and other parameters of the space communication system.

Telemetry Systems

The purpose of this subsection is to consider briefly some of the special telemetry and communication techniques that have been suggested to increase the overall communication efficiency of future space missions. Several references can be consulted by the reader who is interested in obtaining more detailed information concerning the concepts involved, their applications, or the systems that have been proposed to employ the special techniques discussed below.

For general information on space telemetry, references 45 through 50 can be consulted; references 43, 44, and 51 through 56 treat the subject more specifically. References 59 and 63 through 69, and 70 are recommended for obtaining more information on the telemetry and communication systems of the Saturn vehicles and the Apollo mission. References 59, 65, 66, and 69 are especially recommended for the depth of their coverage and the clarity and thoroughness with which they treat the telemetry subject.

A detailed description of the actual telemetry and communication equipment used in the Saturn vehicles is given in the SPACO, Inc., document entitled A Study of the Use of On-Board Information Transfer System for Factory Test and Checkout. Tables 7 and 8, from reference 59, give an estimated list of the tracking, telemetry, and communication equipment under development for the Saturn vehicle and the spacecraft of the Apollo lunar mission.

TABLE 7. APOLLO LAUNCH VEHICLE RF SUBSYSTEMS (ESTIMATED)

Stage	
S-IC	VHF PAM/ FM/ FM TLM
	VHF PAM/ FM/ FM TLM
	VHF PCM/ FM TLM
	VHF SS/ FM/ TLM
	UHF Command Destruct Receiver No. 1
	UHF Command Destruct Receiver No. 2
	UHF ODOP*
S-II	VHF PAM/ FM/ FM TLM
	VHF PAM/ FM/ FM TLM
	VHF PCM/ FM
	UHF Command Destruct Receiver No. 1
	UHF Command Destruct Receiver No. 2
	X-band Mistram
S-IV	VHF PAM/ FM/ FM
	VHF PAM/ FM/ FM
	VHF PCM/ FM
	UHF Command Destruct Receiver No. 1
	UHF Command Destruct Receiver No. 2
IU	VHF PAM/ FM/ FM
	VHF PAM/ FM/ FM
	VHF PCM/ FM
	UHF/ Updata Receiver
	C-band Transponder
	C-band Gloctrac of X-band Mistram*
	X-band Radar Altimeter*

* Probably restricted to R & D flights.

TABLE 8. APOLLO SPACECRAFT RF SUBSYSTEMS (ESTIMATED)

Module	Subsystems
Service/ Command Module	VHF/ FM Transmitter
	UHF Updata Receiver
	S-band Transponder

TABLE 8. APOLLO SPACECRAFT RF SUBSYSTEMS (ESTIMATED) (Cont'd)

Module	Subsystems
	C-band Transponder X-band Rendezvous Radar Transponder HF Transceiver VHF Recovery Beacon VHF-AM Transmitter/ Receiver
Lunar Excursion Module	VHF-AM Transponder S-band Transponder X-band Rendezvous Radar X-band Landing Radar X-band Radar Altimeter
Space Suits	VHF-AM Transmitter/ Receiver

Most of the techniques suggested as possible methods for improving space telemetry and communication systems have as their goal either a more efficient use of the power available or an improvement in the reliability of the system, or both.

Some of the techniques recommended for increasing the data capability of a telemetry system without the addition of transmitters or other equipment are, extremely high-speed sampling techniques, expansion of the total data bandwidth to allow incorporation of additional blocks of sub-carriers or time-multiplex systems, and programming procedures appear to be most promising.

Techniques for improving the reliability of digital space telemetry systems can be considered under three headings, decision feedback, information feedback, and power control [71, 72]. All of these techniques are characterized by the use of the ground station as a control link to the vehicle, making the telemetry system a closed-loop system by the use of this feedback path.

Self-adaptive Systems. One step toward adaptive telemetry systems is the use of programming techniques to conserve transmitter power [61]. For example, a multistage vehicle eliminates some of the subcarrier channels of the multiplex system by a disconnect plug at the time of stage separation and uses of the total transmitter power for the remaining channels. This technique results in an increased signal-to-noise ratio without an increase in transmitter power.

Rather than eliminate the subcarrier channels, the same technique can be applied to transfer the measurement parameters during the different periods of interest such as lift-off, stage separation, payload or spacecraft separation, reentry, etc. For example, in a multistage vehicle the measurements would normally duplicate themselves, in type at least, from stage to stage. With a controlling programmer located between the encoders and the transducers, as shown in figure 15, the capacity of the system can be fully utilized if one channel supplies programmer information and the other channels are appropriately switched from stage to stage. The success of such a system depends heavily upon the reliability of the programmer device.

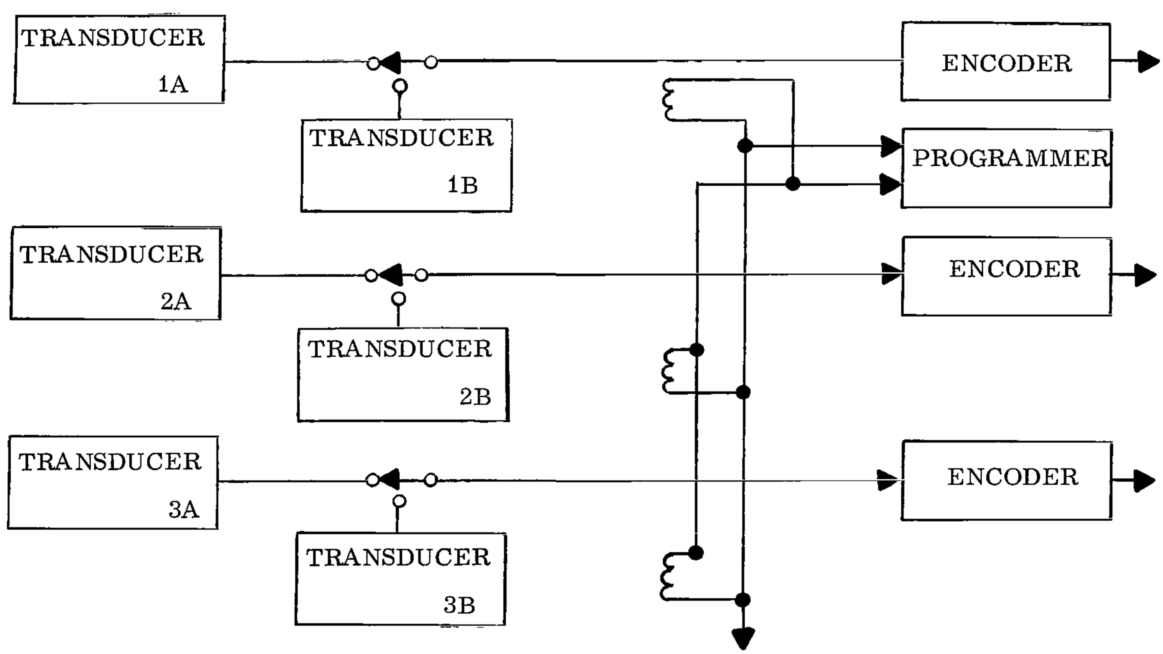

FIGURE 15. PROGRAMMED TRANSDUCER TECHNIQUE

An alternate approach is programmed transmitter power. In long-range applications, the transmitter power is increased at a predetermined point in flight to maintain a desired signal-to-noise ratio over the entire trajectory. This technique has been successful in both space and missile work.

Sometimes the transfer is effected through a command system based on the measured signal received from the vehicle. This transfer system results in a more economical use of battery power and some reduction in the weight and volume of the power supply.

Because information is available only during the periods of interest in the test or mission, additional advantages at the receiving end of the system that are offered by conservation techniques are that less tape recorded and read-out capabilities are required for quick look and data reduction.

At this point it will be useful to recall from the second subsection of section II of this report that the telemetry subsystem of the communication system performs a variety of functions such as: transmitting engineering data that are taken by the spacecraft and used to evaluate spacecraft performance and to perform failure analysis in case of equipment malfunction, conducting certain operations during flight, and collecting automatic checkout data for reliability analysis and evaluation. In almost all cases, some prediction of data rate and amplitude can be made for most of the data collected and telemetered. This fact, then, leads into the next logical step in adaptive telemetry — the use of a device, or a computer program — to examine each of the measurements and reproduce only those data segments which exceed stipulated tolerances [61]. In this way, the system is telemetering only out-of-tolerance data; however, the gaps between such data also supply information, because the absence of data is equivalent to within-tolerance conditions.

The implementation of this approach could take many different paths. One technique, the elimination of measurements after they are no longer of interest and the transfer of new measurements into the same bandwidth slot, has already been mentioned. Another approach would be to use the program technique, enlarged to include the transfer of measurements in a single stage of a multistage vehicle, by utilizing known information concerning the time of various function occurrences. This technique would have to satisfy strict requirements in choosing transfer times and measurement switch-over characteristics, and a highly reliable programmer device would be mandatory.

Conceptually, the next step would be the ideal self-adaptive telemetry system, conceived as an intelligent system which monitors all data before transmission and selects the data to be transmitted at a specific time. This method would require on-board data processing. Depending upon the specific application, any or a combination of all parameters (bandwidth, transmitter power, data rate, etc.) might be controlled. The controlling criteria could be rate of change and amplitude, for example, but other criteria to make decisions could also be incorporated, such as the occurrence time of an event, the duration of an event, etc. Even more sophisticated techniques such as analysis of shock, vibration, and other complex phenomena might be utilized in the system before data selection.

It is clear that such an advanced, self-adaptive telemetry system would require a large storage capacity and the development of special circuitry having an extremely high reliability for handling the large number of operations and decisions on the data to be telemetered. No implementation has been reported, but this brief preliminary look at the possibilities of adaptive techniques would indicate that in the next few years adaptive, or partially adaptive telemetry systems for space missions will come into being. More information on self-adaptive systems can be found in the SPACO, Inc., report by C. E. White, entitled, A Study of Trends in Space Vehicle Digital Information Transfer Systems.

Feedback Systems. Feedback systems can also be considered adaptive systems, but one of the main advantages of using the feedback link is a possible improvement in the reliability of the received information. Such feedback systems comprise decision feedback, information feedback, and power control systems, although compound feedback (in which information and decision feedback are combined) is also possible.

Decision feedback systems employ a means for the receiver to withhold, in doubtful cases, the decision as to which information symbol was sent and to request additional data from the transmitter. Information feedback systems employ a means for the sender to obtain information from the receiver regarding the reliability of the received signal, and to send additional information in doubtful cases. Power control feedback systems use the feedback process to adjust the radiated transmitter power so that the strength of the received signal is always slightly above a set threshold (usually, the expected receiver signal strength at maximum range). Power control, as explained above, is possible without the feedback loop if sufficient information is available concerning trajectory of the vehicle and the resulting propagation losses.

The advantages of feedback telemetry systems, according to references 71 and 72, are twofold. First, the feedback channel can be employed to improve the reliability of the data received (i.e., decrease the error probability) and, second, when the signal-to-noise ratio of the forward channel is fluctuating, the feedback channel can be employed to change the data rate accordingly, permitting the transmission to be matched to the channel conditions (whereas for a non-feedback system the transmission is designed for the worst possible signal-to-noise ratio at which the system must operate). For more details, see references 71 and 72. The development of an adaptive format generator is reported in reference 73. Power versus bandwidth trade-offs for feedback FM systems are considered in reference 42. Details on implemented telemetry systems (adaptive and low-power types) can be found in references 74 and 62, respectively.

Other Telemetry Systems. Two other telemetry systems should be mentioned here; microwave telemetry and pulse-amplitude pulse-code modulation

(PACM) telemetry. Although they are not adaptive or feedback systems, they merit brief consideration as future telemetry links.

Two specific microwave bands have been assigned as future telemetry carriers for aircraft, missile, and space data transmission; 1.435 to 1.535 gigahertz in the L-band, and 2.0 to 2.3 gigahertz in the S-band. Other microwave bands are used for special-purpose instrumentation. The 1.435 to 1.535 gHz band was allocated for aircraft, and the 2.0 to 2.3 gHz band for missile testing and deep space probes (2.200 - 2.290 gigahertz and 2.290 - 2.300 gigahertz, respectively). Standards for operating in the new bands have been prepared by the Inter-Range Instrumentation Group (IRIG) They are adequate for guiding the immediate development and use of microwave telemetry channels. System design considerations and requirements for transmitter, antennas, and receivers are discussed and illustrated in reference 75, which is oriented to missile applications.

The PACM is a hybrid time-division telemetry system with dual accuracy and dual modulation, thus combining the main characteristics of the PAM and PCM systems. The need for such a system stems from the fact that for most missile and space data, high frequency response is usually coupled with low accuracy requirements, while high accuracy data are usually of low frequency content. Consequently, the use of PAM is suggested for those channels handling data that require both low accuracy and high sampling rate, while the use of PCM is mandatory when a need exists to transmit high accuracy data or data already existing in digital form.

In general, it can be stated that PCM offers the best performance in terms of power and bandwidth requirements when accuracies better then one percent are needed, while PAM is preferable when accuracies of one percent or less are acceptable. A detailed discussion of the practical design of a PACM telemetry system (feasibility model) is given in reference 76.

Optical Communication Systems

In this subsection a very brief account will be given of the work being done and the problems involved in using coherent light as a data carrier for general communication and specific communication.

At the heart of these possible communication systems is the optical maser, or laser (acronym for "Light Amplification by Stimulated Emission of Radiation"). The laser provides a coherent light source with high intensity and narrow beamwidth. The word coherent indicates that wideband frequency modulation techniques can be applied, while high intensity and narrow beamwidth are characteristics favorable for space communication.

The specific features of an optical communication system can be considered in the following order:

(a) Beamwidth. It is well known that the minimum width of a radiation beam is determined by diffraction. When light of wavelength λ is used, in an aperture of diameter d, the beamwidth θ (of the major lobe) is:

$$\theta \text{ (radians)} = 1.22 \frac{\lambda}{d} . \tag{21}$$

The beamwidth θ is approximately $0.004°$ for a wavelength $\lambda = 0.7\mu = 7 \times 10^{-5}$ cm (ruby laser), with an aperture of diameter d = 0.5 inch = 1.27 cm. It is clear that in the optical region even small apertures give very narrow beamwidths. This reduces the power required, but the beam must be positioned with extreme accuracy.

(b) Bandwidth. A much wider bandwidth is available at optical frequencies than at microwave frequencies, but at present there are no modulation techniques which would enable this bandwidth to be used effectively. It should also be noted that rather large amounts of optical power will be required to use such large bandwidths, because the energy per photon (which is proportional to the frequency) is relatively large, and the minimum number of photons needed is directly proportional to the frequency band [77].

(c) Propagation. It is expected that optical communication in the earth's atmosphere will be limited to special applications, because of the scattering caused by rain, fog, dust, etc., and absorption by water vapor and carbon dioxide. If all-weather performance is not required, optical systems will probably offer advantages in weight, size, and cost. However, the natural application of optical techniques appears to be in space communication, where "empty" space is almost perfectly dispersion free. In addition to the bandwidth advantage (enormous number of cycles in a small percentage of the visible spectrum), the very narrow beams are far less susceptible to interference by other optical sources.

We can now proceed with a short description of the generation of coherent radiation in the optical region and some of the modulation and detection problems encountered at these frequencies.

Essentially, there are two types of laser generators: the solid-stage lasers, and the gas-phase lasers [78, 79]. Most solid-state lasers, (the first one, reported in 1961, was a ruby laser) are pulsed devices, although experimental work on continuous-wave, solid-state lasers is being conducted in many research laboratories. Gas-phase lasers, containing He-Ne or similar binary gas mixtures, are physically larger than the solid-state devices and provide continuous wave operation, although with a lower output power. Other types of lasers now being actively investigated are the Ga-As injection laser and similar semiconductor-based devices [79]. The resulting radiation in all cases is only partially coherent, with much better coherence in the gas lasers than in the solid-state lasers. This quasi-coherence is good enough to allow near-maximum antenna gain but decidedly not good enough for frequency or phase modulation, or for signal-processing techniques based on phase measurements [80].

Modulation and pulsing of a light source may be carried out in the source itself (internal modulation) or by means of auxiliary devices (external modulation). It is possible to amplitude-modulate or pulse-modulate both incoherent and coherent light. Frequency modulation is theoretically possible for coherent light, but this has not yet been achieved, and all modulating techniques for coherent light use amplitude modulation. Modulation methods under study are described and discussed in references 77, 80, 81, and 82. The most promising modulation method suggested is based on the Pockels, or electro-optical effect, which consists in the change of birefringence produced by the application of an electrical field to a piezoelectric crystal, such as KDP (potassium dihydrogen phosphate) and ADP (ammonium dihydrogen phosphate). The crystal tends to strain whenever an electrical field is applied, (preferably along the crystal's major axis), rotating the plane of polarization of the incident wave. A number of industrial laboratories, including General Electric's Research Laboratory and Electronics Laboratory, are investigating this broad-band, amplitude-modulation technique. For narrow-band information systems, the use of subcarrier modulation is suggested [81].

The detection of coherent light waves is regarded by many researchers to be an even greater problem than modulation. It is believed that detection, not modulation, will determine the maximum bandwidth for optical data transfer systems. The detector in an optical system has to perform a dual task. It must convert radiant energy into electrical energy, and it must demodulate. Ideally, a coherent light detector should have square-law operation, low noise, high conversion efficiency, and fast response [80]. Three basic types of detectors, all based on quantum photoelectric effects, are in use: photoemissive detectors (photomultipliers), in which the absorbed photons cause the release of free electrons from the detector surface, are most efficient in the visible and ultraviolet regions of the spectrum for direct detection of modulation up to 1000 megahertz; photovoltaic detectors, in which the incident photons produce free carriers at the junction of N-type and P-type materials, so that a potential difference is developed; photoconductive detectors, in which the absorbed photons cause the electrons in the valence band or impurity level to move to the conduction band, thus increasing the conductivity of the semiconductor material. The last two types are used mainly in the infrared region.

With the present state-of-the-art, receivers of coherent light signals are of the "crystal video" type (i.e., detector plus amplifier), having modulation bandwidth capability of 100 megahertz. To reduce the effects of internal noise in the detector, as well as noise caused by background radiation, a superheterodyne system has been suggested [77] which would use another laser as a local oscillator, its output being mixed with the incoming signal before reaching the photo-detector. However, the implementation of such a system appears to be in the far future, because it requires a frequency match between a stable, single-frequency, transmitted signal and the signal generated at the local oscillator.

After this brief account of laser systems, it is pertinent to indicate that it is practically impossible to accurately forecast the practical results of present work on lasers and laser communication systems. The use of coherent light for space communication systems appears to be at least a decade away for the following reasons: Knowledge of the propagation characteristics (absorption, scattering, and refraction) of coherent light, and interference by noncoherent radiation (sunlight) is limited; coherent-light optics (mirrors and lenses) are size-limited because optimum performances can be obtained only if extremely close tolerances are observed. These tolerances are about $\lambda/4$ for refractive optics and $\lambda/8$ for reflective optics, compared with tolerances of several wavelengths for ordinary optical devices [80]; Noise power per hertz of bandwidth is several thousand times higher than in rf and microwave systems. Beam pointing, already noted, is a serious problem in Earth-to-space and space-to-space communication. The beamwidth, and hence the power gain, will likely be limited by the stabilization accuracy of space platforms and by the tolerable errors of the servo systems; Doppler shift at light frequencies would be in the range of hundreds to thousands of megahertz. This shift could create at the receiver a serious tuning problem whose solution would require the use of either an extremely large bandwidth or some method of Doppler compensation. Much better coherence than is presently available is required to make feasible the use of phase frequency modulation techniques likely to be needed in space communication systems.

The preceding items are only some of the problem areas that need to be solved before the use of coherent light (infrared to ultraviolet) can be seriously considered as a carrier for space communication. Also, the development of better components and techniques would require a long period of research, experimentation, development, and design before practical systems can be implemented. Of course, economic factors would play a big role in deciding between coherent-light systems and microwave systems. The present trend of long-range communication technology seems to be toward microwave systems. In this connection, note that the costly network of ground stations would have to be greatly modified before it could be used with coherent light communication systems. For Earth-to-space communication systems, an alternate solution could be the use of light as a carrier between the space vehicle and one or more Earth-orbiting satellites, and a microwave or vhf link between the satellites and the ground stations. The ground-station network could still be used, and the disturbing influence of the Earth's atmosphere on light carriers would be avoided by the use of microwave or vhf carriers.

More information on tracking and the acquisition of optical communication systems is given in reference 83. An engineering investigation of the possible use of the ultraviolet region for space communication is reported in references 82 and 84. References 85 and 86 contain a detailed bibliography on masers and lasers. A very readable account of the technology of masers and lasers, including communication and many other applications and economic implications, can be found in reference 87.

Predicted Capabilities

Before considering the predicted growth in the capabilities of future space communication systems, it will be instructive to consider a variety of illustrative communication systems, as specified by the Jet Propulsion Laboratory in reference 9. Each of the applications shown in table 9, taken from reference 9, has unique problems which influence the numerical values chosen for critical parameters of the communication system. Note that these illustrative designs are neither the only designs that could be made to work nor the exact designs that may be built, but they are designs good enough to be used for studying the effects of parameter variations.

For the purpose of this survey, the last four columns of the table are of special interest. The figures in the third column would indicate that real-time television can be sent from the Moon with very little difficulty. The 2.2° vehicle antenna beamwidth is sufficient to illuminate the whole diameter of the Earth: hence the vehicle is not required to track a ground station. When the ground antenna is aimed at the center of the Moon's face, the antenna beamwidth is sufficiently broad to cover the vehicle in its orbit about the Moon. This permits a very simple antenna drive system. With a signal-to-noise ratio of 10 decibels, a bandwidth of 100 megahertz could be used, allowing about 10 frames per second. A special modulation technique, using efficient information coding (FM, PCM, etc.), could be provided.

For a lunar lander with TV (see fourth column), the main differences are a reduction in the lunar vehicle capability (10 watts power, 3.6° beamwidth, 2.5 m^2 vehicle antenna area), and an increase in the ground antenna gain from 4×10^4 to 10^6 (46 to 60 db).

TABLE 9. ILLUSTRATIVE SPACE COMMUNICATION SYSTEMS

Parameter	Weather Satellite	24-Hour Multichannel TV Realy	Lunar Orbiter with TV	Lunar Lander with TV	Mars Orbiter with TV	Cosmic Ray Probe at Edge of Solar System
Range, km	4×10^3	4×10^4	4×10^5	4×10^5	4×10^8	4×10^{10}
Ground antenna gain	10^{3*}	3.5×10^5	$4 \times 10^{4*}$	10^6	10^6	10^6
Vehicle antenna area, m^2	0.05	0.1	7	2.5	100	100
Vehicle antenna beamwidth, deg	omni*	18^*	2.2^*	3.6^*	0.6^*	0.6^*
System Temperature °K	400	300	220	400	100	100
Vehicle radiated power, watts	200	100	50	10	150	150
Frequency region, kmc	0.1 - 0.4 (0.38)	1 - 10 (2.3)	1 - 10 (2.3)	1 - 10 (2.3)	1 - 10 (2.3)	1 - 10 (2.3)
Video bandwidth for $P_r/N=10^3$ Hz	4×10^6	20×10^6	10^6	10^6	2.5×10^3	too small
Video bandwidth for $P_r/N=10$	not used	not used	10^8	10^8	2.5×10^5	25
Time for vehicle to reach destination	20 min	2 hr	3 days	3 days	200 days	30 yr

* Geometric constraint

NOTE: $\Delta\,\theta = 46\,\dfrac{\lambda}{\sqrt{A}} = \dfrac{164}{\sqrt{G}}$

For a Mars orbiter with TV (see fifth column in table 9), the vehicle must keep its antenna pointed at the Earth within a fraction of a degree (a strict requirement for the space vehicle attitude-control system). In case this requirement proves too difficult to achieve, a probable trade-off would be to reduce the antenna area (thus increasing the vehicle antenna beamwidth) and to accept a reduced video bandwidth as a result. An alternate, more expensive trade-off, would be to use a lower transmission frequency which would require a larger ground antenna but the same amount of gain and would retain the original system capability.

Finally, the system for the cosmic-ray probe at the outer limits of the solar system is essentially the same as for the Mars orbiter. The main difference is that the increase in distance by a factor of 100 is compensated by a great reduction in information transmission rate (i.e., bandwidth) and quality.

Table 10, also prepared by the Jet Propulsion Laboratory, indicates the predicted net growth potential of space communication systems. It can be seen from this table that reasonably good television signals can be transmitted from a spacecraft operating near Mars or Venus to the earth circa 1968. This statement, of course, assumes that improvements in the DSIF adhere to program schedules.

CONCLUSIONS

This report gives the systems checkout engineer an overall view of space communication systems and an idea of how they have been developed and implemented. It is hoped that an appreciation of the ways in which such systems are likely to develop during the remainder of this decade will be gained.

A comprehensive picture of the factors that determine the basic parameters of a space communication system is given along with a brief review of the fundamentals underlying the present space communication technology.

The present state-of-the-art in space communication can handle all the communication needs of lunar missions, including the transmission of television and voice channels besides tracking, telemetry, and command functions. It can also satisfy the basic communication needs of unmanned planetary missions to Mars, and in the very near future to Venus, provided the attitude-control system of the space vehicle can keep the narrow beam of the vehicle's antenna pointed at the Earth.

TABLE 10. PREDICTED LONG-TERM SYSTEM CAPABILITIES

Characteristic	1960	1962	1964	1966	1968
Transmitter Power					
Ground	10 kw	10 kw	10 kw	100 kw	100 kw
Spacecraft	10 w	25 w	100 w	1 kw	1 kw
Antenna Gain					
Ground	46 db	46 db	54 db	64 db	64 db
Spacecraft	6 db	20 db	30 db	30 db	40 db
Receiver Sensitivity					
Ground	300°K	100°K	40°K	40°K	20°K
Spacecraft	2000°K	2000°K	400°K	400°K	400°K
Information Bandwidth					
Telemetry					
(10 db Signal-to-Noise Ratio)					
Satellite Application	3.5 kHz	1 MHz	1 - 10 MHz	1 - 10 MHz	1 - 10MHz
Lunar Application	3.5 kHz	1 MHz	1 - 10 MHz	1 - 10 MHz	1 - 10MHz
Mars Application	____	100 Hz 18 dB S/N	10 kHz	1 MHz	1 - 2 MHz
Venus Application	____	400 Hz	40 kHz	1 - 4 MHz	1 - 8 MHz
Edge of Solar System	____	18 db S/N	10 Hz	1 kHz	2 kHz

NOTE: The figures for 1960, 1962 and 1964 are given here only to make the trend in system parameters improvement more meaningful.

Both ground station and vehicle antenna gains can be improved by several decibels. Spacecraft transmitter power can be greatly increased when current investigations of new power sources make these sources available for practical use. More efficient telemetry and encoding systems are very possible within this decade. Coupled with a lowering of the effective noise temperature of the complete system, these advances would provide a much wider bandwidth, and hence a far greater information rate than that of present systems. With this increased capability expected within the next five to seven years, the whole range of needs for the space missions considered in this survey can be reasonably satisfied.

The increased performance thus made possible would indicate that, as far as the communication channel is concerned, reliable transmission of automatic checkout data at high rates and at lunar and near-planet ranges would be feasible for space communication systems by the end of this decade. The important aspects of checkout data handling at the spacecraft and data processing at the receiving station were not within the scope of this survey.

George C. Marshall Space Flight Center
National Aeronautics and Space Administration,
Huntsville, Alabama, June 30, 1965

APPENDIX

LIST OF FORMULAS

Formula Number	Formula Expression	Description	Page No.
1	$G = (\pi D/\lambda)^2$	Gain of uniformly illuminated circular aperture of diameter D, over isotropic radiator	10
2	$G = \frac{1}{2}(\pi D/\lambda)^2$	Practical gain assuming 50 percent efficiency	11
3	$\theta = 165/\sqrt{G}$	Beam width (degrees) of parabolic antenna of gain G	12
4	$L = D^2/16R^2$	Space attenuation between an isotropic radiator and an ideal parabolic antenna of diameter D at a distance R	13
5	$L = D^2/32R^2$	Space attenuation between an isotropic radiator and a practical parabolic antenna of diameter D at a distance R	13
6	$L = \frac{\pi^2}{64} \cdot \frac{D_1^2 D_2^2 f^2}{R^2 c^2}$	Space attenuation between two parabolic antennas of diameters D_1 and D_2 (f=frequency, c=velocity of light)	13
7	$f_d = f_o \frac{\sqrt{1-\beta^2}}{1+\beta}$	Doppler frequency received when source radiating with frequency f_o, is directly receding from the receiver with velocity v (β=v/c, c=velocity of light)	19
8	$f_d = f_o \frac{\sqrt{1-\beta^2}}{1-\beta}$	Doppler frequency received when source is moving directly toward the receiver	19

Formula		Description	Page No.
Number	Expression		
9	$P_n = kTB$	Noise power received from source at absolute temperature T, using a bandwidth B Hz (k=Boltzmann's constant)	20
10	$P_n = kTB(NF)$	Noise power generated within a receiver of noise figure (NF), at absolute temperature T	24
11	$T_r = 290(10^{NF/10} - 1)$	Effective noise temperature of receiver with noise figure (NF)	25
12	$T_r = T_{r_1} + \frac{T_{r2}}{G_1}$	Effective overall noise temperature of two-stage amplifier (G_1=gain of first stage; T_{r_1} and T_{r_2}, effective noise temperature of first and second stage, respectively)	25
13	$P_n = kT_r B$	Effective noise power generated within the receiver	26
14	$C = B \log_2 (1 + \frac{P}{N})$	Channel capacity, in bits/second, of communication channel of bandwidth B Hz, perturbed by gaussian noise (P=average signal power; N=average noise power)	29
15	$C = B \log_2 (1 + \frac{P}{k\,TB})$	Channel capacity when k TB is substituted for N in equation (14)	30
16	$C = 1.44 \frac{P}{k\,T}$	Channel capacity when $\frac{P}{k\,TB} \ll 1$	30
17	$P = 0.693\ k\,TC$	Minimum signal power required for a channel of capacity C bits/second	30

Formula Number	Formula Expression	Description	Page No.
18	$p=0.956 \times 10^{-23} T$	Minimum energy required per bit of information received	30
19	$M+1=\frac{P(FM)}{P(FMFB)}$	Ratio between transmitter power required by FM and FMFB systems (M=modulation index of FM system)	45
20	$P_R=\frac{P_T}{\lambda^2}\cdot\frac{\eta_T A_T \eta_R A_R}{R^2}$	Power received by an antenna of area A_R and efficiency η_R from a transmitter having an antenna of area A_T and efficiency η_T, radiating a power P_T at a wavelength λ	44
21	$\theta\,(\text{radians})=1.22\,\frac{\lambda}{d}$	Beamwidth created by diffraction by an aperture of diameter d on radiation of wavelength λ.	54

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A paper that discusses frequency and time division multiplex and leads to a proposal of an FM/AM system to replace the FM/FM system. See also reference 37, which reaches the opposite conclusion and reference 45, whose conclusion agrees with it.

50. Whitehead, E. D.; and Walsh, J.: Radio Telemetering. Proceedings of Institute of Electrical Engineers, Vol. 100, No. 64, March 1953, pp. 45-59.

A comprehensive discussion of earlier space telemetry systems dating to 1953, together with a discussion of modulation systems, transmitting and receiving equipment, transducers, and overall system and considerations.

51. Philco Corporation: A Telemetry Improvement Study. Philco No. WDL-TR1909, October 1962.

A highly theoretical paper which deals with the possible applications of digital filtering techniques to improve the telemetry of the Advent Satellite (PCM/PM/PM). Investigation of adaptive techniques is reported in detail.

52. Philco Corporation: Study and Experimental Investigation of Sampling Rate and Aliasing in Time-Division Telemetry Systems. Aeronautic Report No. ASD-TR-61-553, AD 278515, June 1962.

Reports the results of a study (analytical and experimental) undertaken for the United States Air Force to determine the effects of data power spectrum and system design parameters on aliasing and data interpolation errors. The results are applicable to time-division multiplexed telemetry systems (PAM/FM, PDM/FM, and PCM/FM).

53. Johnson, C. M.; and Gruenberg, E. L.: Semi-Active Communication System for Satellite Telemetry, NASA Catalog No. A63-16518.

Report on a communications system for satellite telemetry which eliminates the need for on-board transmitter and offers, according to the authors, significant advantages in reliability, vehicle power, communications privacy, and operational simplicity.

54. Christie, C. B.: General-Purpose PCM Telemetry Processor Handles Present and Future Mission Requirements, Electro-Mechanical Research, Inc. Report No. TP063-1.

An interesting paper for the insight it gives into the design problems of a general-purpose PCM data processor flexible enough to handle a variety of present and anticipated PCM formats.

55. Ellis, Donald H.: A Universal PCM Data Transmission System. Proceedings of the 1961 National Telemetering Conference, Paper No. 14.

Describes the development of an engineering model of a vehicle-borne PCM telemetry system, where operational flexibility and efficiency were the main design considerations. This Dynatronics report of a study conducted for the United States Air Force indicates that the flexibility of the system is attained by the ability to change some parameters (like transmitter power, bit rate, and acquisition format) a reasonable number of times in flight upon command.

56. Walker, C. A.: The General Purpose Computer as a Telemetry Ground Station. Proceedings of the 1962 National Telemetering Conference, Paper No. 14-4.

An excellent paper in an educational sense, which explores the general requirements of telemetry ground stations and the suitability of small, high-speed, digital computers to satisfy these requirements.

57. Martin, B. D.: The Mariner Planetary Communication System Design. JPL Technical Memo No. 33-38, Paper No. 8-3 of the Proceedings of the 1962 National Telemetering Conference.

Contains recent contributions by JPL to space communication concepts and technology.

58. Truszynski, G. M.: Space Communications. NASA Office of Tracking and Data Acquisition, NASA Catalog No. N63-12295.

A good description of NASA's ground station networks for unmanned space missions, deep space missions, and manned satellite missions.

59. Fordyce, S. W.: Communications and Tracking on the Apollo Lunar Exploration Mission, National Aeronautics and Space Administration, October 1963.

This paper, presented at the 1963 National Space Electronics Symposium (Miami, October 1-4, 1963), describes the current plans for the communication and tracking links between the Apollo space vehicle and the Manned Space Flight Network being developed by NASA. It gives a brief overall view of the communication requirements of the lunar mission, including radar tracking, voice communication, telemetry, and command links.

60. National Aeronautics and Space Administration: Proceedings of the NASA-UNIVERSITY Conference on the Science and Technology of Space Exploration, NASA, NASA SP-11, November 1962.

Chapter 26, "Data Acquisition at Planetary Ranges", which has already been mentioned as reference 12, and Chapter 46, "Power for Spacecraft" are particular significance to this report.

61. Lowy, M. A.: An Approach to Self-Adaptive Telemetry Systems. Proceedings of the 1961 National Telemetering Conference, Paper No. 10.

A brief introductory paper on the subject, which gives very good background information.

62. Choate, R. L.: Design Techniques for Low-Power Telemetry. JPL Technical Report No. 32-153, March 1962.

This paper develops a direct approach to the design of minimum-power telemetry systems utilizing a phase-locked PM (phase-modulated) demodulator, for lunar missions requiring either narrow-bandwidth telemetry or voice communications. A concise, substantial treatment.

63. Hoberg, O. S.: Saturn Telemetry and Tracking. Astronautics, February 1962.

A comprehensive but concise description of the Saturn telemetry and communication system, its development, and design.

64. Eichelberger, R. P.: The Saturn Telemetry System. Proceedings of the 1962 National Telemetering Conference, Paper No. 13-1.

An excellent but brief discussion of the Saturn telemetry system from an overall data systems approach. The three basic telemetry techniques used for the Saturn vehicle (FM/FM, SS/FM, and PCM/FM) are described as applied to each stage of the vehicle, including the instrument unit. Possible use of the telemetry system for vehicle monitoring and checkout is also briefly considered.

65. Rorex, J. E.; and Frost, W. O.: Telemetry Considerations for Large Space Vehicles. IRE Transaction on Space Electronics and Telemetry, Vol. SET-8, No. 2, June 1962.

This excellent paper is a "must" because of its clear and broad coverage of the most important problem areas encountered in large space-vehicle telemetry systems. Data acquisition and transmission for automatic vehicle monitoring and checkout is discussed in detail. Observations are also made on some signal processing techniques, predetection recording, and adoptive techniques as possible trends in future space telemetry systems.

66. Frost, W. O.: SS/FM: A Telemetry Technique for Wide-Band Data. IRE Transactions on Space Electronics and Telemetry, Vol. SET-8, No. 4, December 1962.

A detailed description of the background and phisosophy of SS/FM. It is followed by a general description of the SS/FM vehicle and ground telemetry equipment utilized in the Saturn vehicle program and a summary of system characteristics and performance.

67. Ratner, V. A.; and Eichelberger, R. P.: Predetection Recording System for Saturn Telemetry. NASA Catalog No. A63-16520.

Reports a predetection recording system designed to provide a capability to receive and store a wide variety of telemetry formats, the basic design criteria being extreme flexibility and simplicity of operation. The system design was established around four basic concepts: linear signal processing, wide-band recording, frequency translation (to make demodulation compatible with wide-band recording), and longitudinal recording.

68. Marshall Space Flight Center: Telemetry Systems Handbook for Saturn Space Vehicles. 1963.

This MSFC internal document provides an informal, unofficial source of information on telemetry systems that are planned and in the process of development for the Saturn V vehicle. Many of the techniques described are being applied to vehicles SA-6 and subsequent vehicles of the C-1 configuration. Initial emphasis is placed on system and design details relating to the adaptation of the telemetry system to automatic checkout. Great detail is provided on the PCM/DDAS telemetry assembly, including internal design details and interface parameters with other assemblies. The document deals mainly with vehicle-borne equipment and not with GSE.

69. Frost, W. O.; and Smith, C. D.: Saturn Telemetry. Marshall Space Flight Center, 1962.

Another MSFC document, for internal use only, that describes the telemetry systems for the Saturn vehicle and gives a brief history of the preceding systems. Its 53 pages (29 pages of text, 24 pages of illustrations and diagrams) include: I. History and background; II. Principles and problems of telemetry; III. Saturn telemetry systems (FM/FM, PAM/FM/FM, PDM/FM/FM, SS/FM, PCM/FM, PCM/SS/FM, and UHF/FM); IV. Saturn vehicle telemetry (vehicles SA-1 through SA-10); V. Developments; VI. Summary. This reference is a "must" for a detailed account of the Saturn telemetry systems.

70. Marshall Space Flight Center: MSFC Automation Plan. MSFC, May 1962.

Subsection C, "Data Acquisition for Vehicle Monitoring and Checkout", is pertinent to our survey.

71. Harris, B.; and Sommer, R. C.: Some Recent Advances in Adaptive Digital Telemetry Systems. Proceedings of the 1962 National Telemetering Conference, Paper No. 10-5.

The paper summarizes an academic study of three techniques suggested for improving the reliability of digital space telemetry systems: (1) decision feedback; (2) information feedback; and (3) power control. No implementation is reported.

72. New York University: Feedback Communication Systems - Summary Scientific Report. NYU Report No. AFCRL-62-921, AD 292119, November 1962.

Summarizes the studies done for the United States Air Force on feedback communication systems. The contents of eleven scientific reports are described, most of them dealing with: (1) theory and development of coded, error-free, feedback communication systems; (2) signal theory, especially an applied feedback communications; and (3) analysis of system performance.

73. Gottfried, R. E.; and Marsh, G. F.: Adaptive Telemetry Format Generator. Proceedings of the 1962 National Telemetering Conference, Paper No. 10-1.

Reports the development of an adaptive format generator that can supplement many existing telemetry and data acquisition systems by providing these systems with the ability to change adaptively both the sampling rate and the choice of signal inputs. The logic and implementation of the device are described in detail.

74. Dynatronics, Inc.: Adaptive Techniques for Long Range Transmission of Pulse Code Modulation Telemetry Data. Dynatronics Technical Report No. ASD-TR-61-198, AD 288076, August 1962.

Reports the results of a study of techniques for long-range transmission of PCM telemetry data, performed by Dynatronics for the USAF. The development of a system design concept and an engineering model of a vehicle-borne PCM telemetry system are presented with great care and detail. Operational flexibility (adaptability) and efficiency are stressed as the main considerations in design. Emphasis is in the area of controlling system parameters that contribute to the range capability of the system. This "thick" report may be of interest to the electronics design engineer.

75. Bigelow, G. F.: Status of Microwave Telemetry Implementation. NASA Catalog No. A63-16517.

Considers an implementation plan for microwave telemetry (the assigned bands are 1.435 to 1.535 gHz in the L-band, and 2.2 to 2.3 gHz in the S-band) and discusses current system capability and the solutions to the problems created by the new frequency allocation.

76. Pastor, G. J.: Practical Design of PACM Telemetry Equipment. Proceedings of the 1962 National Telemetering Conference, Paper No. 13-4.

Deals with the derivation of the important parameters in PACM telemetry and the logical design of a feasibility model based on the derived parameters. The concept of PACM (hybrid Pulse Amplitude and Pulse Code Modulation) is briefly explained.

77. Smith, A. W.; and Williams, G. W.: An Initial Assessment of Cummunication Systems at Optical Frequencies. DRTE Report No. 1071, AD 259932, June 1961.

A comprehensive report issued by the Defense Research Telecommunications Establishment of Canada which contains a preliminary evaluation of communication and radar systems at optical and near-infrared frequencies. Its 14 information-packed pages review the state-of-the-art (as of middle 1961) of optical masers, modulators, and receivers. Possible applications are considered for Earth surface and space communications, and tentative suggestions for development of better components and techniques are formulated.

78. Oliver, B. M.: Some Potentialities of the Optical Maser. Proceedings of the Institute of Radio Engineers, Vol. 50, No. 2, February 1962, pp. 135-141.

An introductory paper on the principles and possible applications of the optical maser. Methods for generating, focusing, and collimating coherent radiation are described. The use of lasers for communication is explored and certain medical and other applications are suggested.

79. Raytheon: Lasers: State of the Art. Electronic Progress, Vol VII, No. 4, January-February 1963.

This booklet (29 pages) contains four sections on lasers and one section on laser applications. Four types of lasers are described and discussed: pulsed solid state lasers, gas phase lasers, experimental CW solid state lasers, and GaAs injection lasers. The applications section deals with the ground systems and the space systems separately. This last part clearly discusses the possible applications and limitations of laser systems in space communications and indicate the many problems still to be solved.

80. Holahan, J.: Coherent Light as Data Carrier. Space Aeronautics. April 1962, pp. 97-109.

This excellent paper is recommended for its very practical, informative account of the advantages and disadvantages of data transmission at optical frequencies (high directivity, spectral purity, coherence, and large information bandwidths as against attenuation, noise problems, and pointing requirements). The theory that light is an information carrier is outlined simply; the basic components of coherent-light systems (generators, modulators, and detectors) are reviewed; and several proposed system applications are analyzed. Sketches, graphs, and tables are freely used throughout the paper.

81. The University of Michigan: Investigation of Optical Spectral Regions for Space Communications. Institute of Science and Technology, AD 287640, May-July 1962.

Reports the program objectives and the results of a study conducted for the United States Air Force to determine the suitability of the spectral region between 0.2 and 100 μ (middle ultraviolet to middle infrared) for space communications. The detailed treatment of the subject (covered in some 190 pages) is best suited to the needs of the research and/or design engineer in optical communications.

82. Bailey, D. S.: Technical Note on Optical Communication I. JPL Report No. A24-2, AD 261583, May 1961.

This report presents the results of a communication potential investigation of systems operating in the visible and ultraviolet region of the optical spectrum (wavelengths between 10,000 and 3,000 Angstroms). The thorough coverage of the report is primarily academic and educational and such is valuable.

83. Anderson, R. F.: Study and Investigation of Acquisition and Tracking of Optical Communication Systems. Philco Interim Engineering Report No. 3, AD 273273, February 1962.

Reports progress on the study and investigation of acquisition and tracking for two hypothetical, optical, space-communication links: earth satellite and lunar satellite, and earth satellite and space vehicle. The development of techniques and configurations and an investigation of specific items which affect the selection of techniques and configurations are discussed. May be of interest to the optical communications design engineer.

84. Glatt, L.: Parameters Pertinent to the Detection of Ultraviolet Radiation in Space-to-Space Configurations. Space Technology Lab Report No. 6110-7244-RU-000, AD 281910.

The use of the UV region below 2800 Angstroms is investigated for its possible application in passive space-to-space surveillance and the active transmission of secure messages between friendly spacecraft. A review of the most basic and general systems parameters, and of the physical considerations which determine these parameters, is presented. The report concludes that the outlook for broadcast communications in space via an ultraviolet band carrier does not appear promising unless greatly improved UV sources can be developed.

85. Goldmann, J. B.: Optical Communications: A Bibliographic Survey of Possible Space and Terrestrial Applications of the Laser and Maser. Lockheed Report No. 3-77-62-4/SB-62-7, AD 275591, March 1962.

This annotated bibliography includes 157 publications released from 1959 through February 1962.

86. ASTIA: Masers and Lasers: A Report Bibliography. AD 271100, February 1962.

Contains documents cataloged by ASTIA from 1955 through January 1962 and is limited unclassified, unrestricted references. The classified references have been issued in the secret document AD 327897. Some 310 documents are reviewed in the present bibliography.

87. Hogg, C. A.: Masers and Lasers. Maser/Laser Associates, 1962.

This book contains a clear explanation of the principles and applications of masers and lasers. This research report - which carefully avoids unneeded technicalities - is the work of a group of students at the Harvard Graduate School of Business Administration, written during the academic year 1961 - 1962. Its 200 pages are evenly balanced between principles and applications.

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A brief treatment of the communication problems at lunar and interplanetary distances.

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