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Limitations on lasers for deep-space communication

Because of the increased efficiency made possible by narrower beam widths at visible-light frequencies, laser communication systems have certain advantages over conventional radio systems. However, unless elaborate and costly precision tracking gear is used, extremely narrow beam widths prohibit high reliability of reception. The 8- to 13-micron infrared range is considered to be optimum for space communications

There is today considerable enthusiasm for the potential applications of the laser. News headlines herald future uses for lasers in communication, guidance, medical applications, the machining and welding of materials, and even as a death ray. In fact, the development of the laser is expected to share equal importance with the development of the transistor.

In view of the current feeling, it seems almost blasphemous to suggest that the laser does have certain fundamental limitations that restrict its applications. Actually, the writer shares the optimism about future applications of the laser, but not so much in the prophesied applications as in the undiscovered and unexpected applications. For example, the use of lasers in optical data processing and data display may be an important application, even though it has not been widely publicized.

Unquestionably, the laser will have important applications for terrestrial communication services because of its extremely high channel capacity. Its application for space communication, however, must be examined. It is always very difficult to decide on the particular communication system and the optimum operating frequency range for space communication, because the choice depends on so many practical considerations (such as type of service, range of communication, size and weight of equipment, initial equipment cost versus continued operating costs, and other secondary considerations).

To establish ground rules in this comparison of laser communication to conventional radio communication, the term "laser communication" implies any highly coherent communication system operating at frequencies higher than approximately 120 gigacycles, for which present conventional equipment is not available.

To exclude comparisons based on the present state of the art, it will be postulated that future development of lasers has already occurred, that they operate at any chosen frequency range, that they are highly coherent continuous-wave generators of electromagnetic wave radiation, and furthermore that they have the same output power and efficiency in converting power supply energy to radiation energy as do conventional radio and microwave generators. Thus, one practical limitation on lasers for present (and probably near-future) space communication is that the operating frequency is not arbitrary and that most lasers are not highly coherent, cw-operating, efficient generators. It is readily conceded, however, that the state of development will vastly improve in the future. The final ground rule is that the optimum communication system is considered to be that system which transfers a given rate of information with minimum power supply energy.

The importance of establishing ground rules in evaluating different communication systems should be emphasized. The intended service objectives establish the ground rules to be used in comparing different systems. For example, the rule that the optimum system is that which transfers the maximum quantity of information at minimum cost is a valid one for certain service objectives. It could lead to the result that the direct, physical transfer of recorded information is the optimum communication system. Consequently, the established ground rule will depend on those objectives that the communications systems designer considers to be most important. The most common service objective is to transfer a given rate of information with the least expenditure

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of power-supply energy. It also is pertinent to add the phrase "with a given reliability of reception."

THE PHOTON ENERGY EFFECT

Because it has been agreed to assume that laser systems have the same communication characteristics as radio systems (namely, cw coherent operation), the optimum operating frequency range for any system is the actual objective according to the above ground rule. Moreover, power supply requirements for the receiver are assumed negligible for any system, but the signal-to-noise characteristics of the receiver are highly important in evaluating a given system.

Suppose there are two communication systems in free space: one operating in the microwave region at frequency ν_1, and the other in the visible light region at frequency ν_2. Let the radiation from the transmitters be omnidirectional and let the receivers for both systems be located at the same range from both transmitters. Since an electromagnetic wave can be equivalently represented as a distribution in photons, the receivers will be considered to be receiving photons of radiation energy. Furthermore, they will be considered ideal in the sense that they

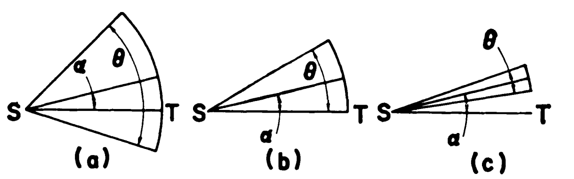

Fig. 1. Detection reliability vs. beam width

are capable of receiving individual photons of signal energy well above their internal noise level. Finally, the range for the receivers is set sufficiently far that both have the same average statistical probability of receiving one photon out of each pulse burst of photons radiated by the transmitters.

Let the chosen information rate be the Morse code letter *S*, consisting of three pulses or bursts of photons radiated in one second by both transmitters. The total energy required from the power supply per second to radiate the total of *N* photons in the three pulses is

$$E = \frac{Nh\nu}{\eta} \text{ joules} \tag{1}$$

where

h = Planck's constant
ν = frequency
η = conversion efficiency

In this expression, all quantities are constant except the frequency. Consequently, for the same rate of information transfer, the optical system will require ν_2/ν_1 times the power supply energy required by the radio system. As a spectacular example, an optical system at 6,000 angstroms would consume a million times the power required by a 500-mc microwave system in this idealized experiment. Of course, the very important practical consideration of system efficiency gain using directional antennas and the question of receiver noise characteristics were not considered in this idealized experiment; it was described merely to illustrate this important aspect of communication efficiency.[1] As Oliver has pointed out, communication efficiency tends to decrease with the first power of frequency (because of this photon energy effect) and to increase by the square of the frequency (because of the antenna gain effect) when a fixed-diameter parabolic antenna is employed.[2] Consequently, the net efficiency of a communication system should increase with the first power of the frequency, except for another practical limitation that sets in at high frequencies.

THE OPTIMUM ANTENNA DIAMETER

Consider an electromagnetic source radiating in a beam width θ in the general direction of a target receiver (Fig. 1). No matter how excellent the aiming equipment, there is always a finite tracking error angle α. If the beam width is sufficient, the reliability of detecting the signals is extremely high; see Fig. 1(a). As the beam width is decreased to the configuration shown in Fig. 1(b), the target receiver is included just within the beam, and detection reliability depends on how accurately the maximum tracking error and the receiver target position are known. When the beam width is made extremely narrow, the reliability for detection is quite low; see Fig. 1(c). It seems reasonable to consider the configuration of Fig. 1(b) as a criterion for the maximum diameter of a well-designed parabolic antenna or mirror. Because highly coherent radiation is assumed, the maximum and optimum antenna diameter *D* may be determined from

$$\theta = 2\alpha = \frac{1.22\lambda}{D} \tag{2}$$

It is noted that this is an angular relationship; the distance to the receiver, or range, has no bearing on this aspect of detection reliability.

RELATIVE COMMUNICATION SYSTEM EFFICIENCY

Next, the question of receiver noise must be considered. The microwave maser closely approximates an ideal quantum amplifier, and visible light detectors as well. Stranberg's relation for noise power spectral density[3] is

$$\psi(\nu) = h\nu\left[1 + \left(\exp\frac{h\nu}{kT} - 1\right)^{-1}\right] \tag{3}$$

The number of noise photons produced at the receiver per second is $\psi(\nu)/h\nu$, and the reciprocal of

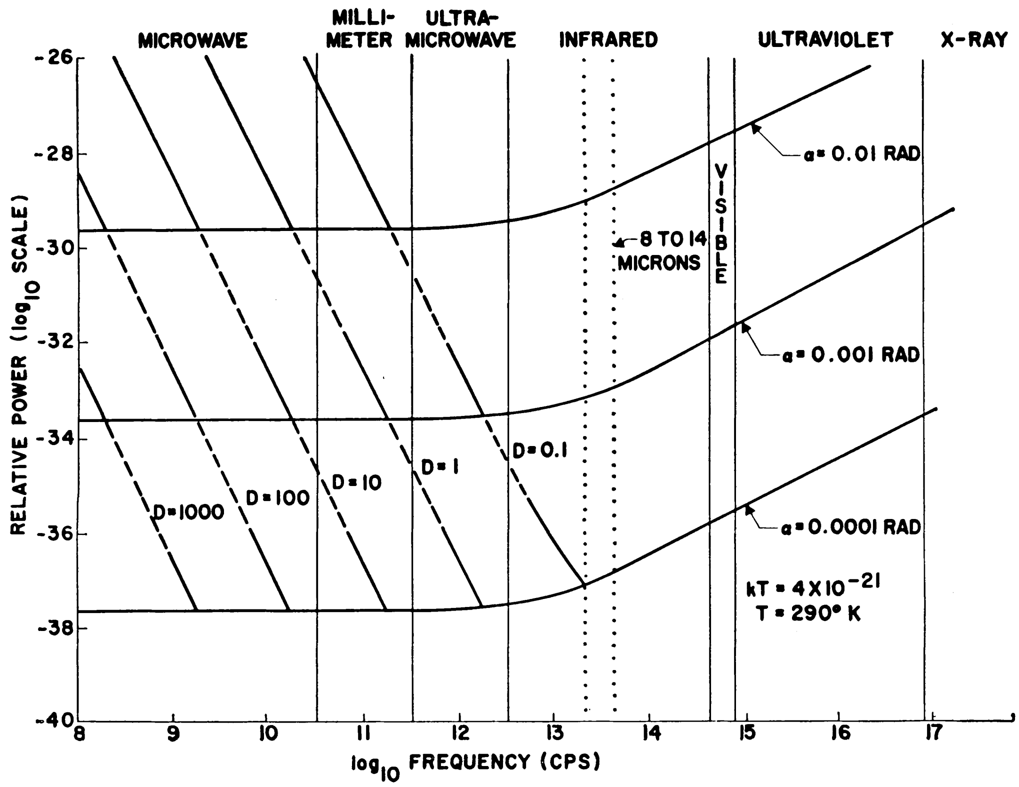

Fig. 2. Relative required power for communications, with fixed antenna diameters and fixed beam widths

this expression is the S/N ratio for reception of one signal photon per second. Hence, to produce a given S/N ratio, the number of photons in an emitted pulse, which would otherwise produce one photon per second at the receiver, must be multiplied by the factor $(S/N)\psi(\nu)/h\nu$. In addition, if two systems are to be compared, the information rate in terms of bandwidth B must be the same for both. Finally, the transmitting and receiving antenna systems are assumed to have matched gains, so transmitter power requirements may be reduced by the factor $\sin^4 \theta/4$. Consequently, the net power required from the power supply for a given information rate may be stated as

$$P_s = (S/N)\ NB\ \psi(\nu)\ (\sin^4 \theta/4)/\eta \qquad (4)$$

Because the quantity $(S/N)\ NB/\eta$ is the same for both systems, the comparison between two systems may be made on the basis of normalized relative power,

$$P_n = \psi(\nu)\ \sin^4 \theta/4^* \qquad (5)$$

Moreover, because the range and bandwidth are the same for all systems in this comparison, the efficiency of the system decreases as P_n increases. This function is plotted against frequency (Fig. 2) for two conditions: (1) antenna diameters held constant and (2) antenna diameters adjusted to the optimum size to produce a beam width of twice the minimum tracking error angle indicated by equation 2.

To interpret the meaning of this family of curves, consider an example wherein a systems designer possesses an antenna diameter of 10 meters and equipment operating at 1 gigacycle. He could improve the efficiency by operating at higher frequency, say 1.83 gigacycles. Suppose, however, that his tracking gear is not very precise or that he does not know the position of his receiver to better than 0.01 radian (about 0.57 degree). He is forbidden to operate at higher frequency to obtain higher efficiency without sacrificing reliability of reception. He could, however, use a smaller, lighter antenna of one-meter diameter at a higher frequency with no appreciable change in efficiency, other than practical considerations such as the variation of conversion efficiency, power to drive the tracking gear, and decrease in equipment weight. He probably would not use the laser at visible light, because the communication efficiency is much lower and he is forbidden to make use of the narrow beam widths that the laser is capable of producing.

If the tracking can be made more precise, say, 0.001 radian, a further improvement in efficiency is obtainable and the same arguments apply, except that the antenna diameter must be larger at a selected microwave or millimeter-wave frequency.

If it is possible to produce exceptional precision

*Subsequent to the publication of this article, it was pointed out to the author that greater generality would result by assuming a *large receiver* antenna of arbitrary size rather than matched antenna gains. This would modify equation 5 to read $P_n = \psi(\nu) \sin^2 \theta/4$. A replot of Fig. 2 based on this condition would change the relative power scale and slope of the constant-antenna-size curves, but the general results would be essentially unchanged. The original assumption of matched antenna gains remains valid for two-way communication.

in tracking indicated by the $\alpha = 0.0001$ radian limiting curve, the designer may prefer the less efficient laser system with a small antenna rather than a 100-meter-diameter antenna in the microwave region or a 10-meter-diameter antenna in the millimeter region. However, the same efficiency as a laser system could be obtained by operating with an antenna diameter of between 1 and 10 meters.

It is possible to aim beams with much higher precision than considered here. To do so, however, requires not only extremely elaborate and expensive precautions, but also an exact knowledge of receiver position to the same precision. The systems designer may find that providing extremely high tracking precision to take advantage of laser systems with narrow beam width may result in higher costs than would a relatively small antenna producing a broader beam with conventional radio-type equipment.

It is true that the laser system is capable of much higher channel capacity than the conventional radio system, and it has been argued that another important advantage of laser communications will be relief of the crowded frequency spectrum. However, this phenomenon is strictly terrestrial; in space, the entire radio-frequency spectrum may be used over and over again without interference if reasonable beaming techniques are employed.

CONCLUSIONS

The preceding arguments lead to the viewpoint that laser communication systems will not be employed in space communications as extensively as initially supposed—even when highly coherent cw-operating and high-conversion-efficiency devices are developed. There is one important exception to this viewpoint: an examination of the curves in Fig. 2 indicates that a laser system operating in the 8- to 13-micron range of the infrared region, where an atmospheric window exists, may provide the most efficient communication system. In addition, practical factors ordinarily considered to be of secondary importance could, in some instances, override these more basic considerations.

The following points may summarize more succinctly the present viewpoints held on space communications:

1. The optical maser can be used in deep-space communications in those special cases where the receiver position is known with sufficiently high precision to warrant the use of extremely narrow beam transmission and tracking gear of exceptional quality.
2. In general, highest communication efficiency is obtainable at radio and microwave frequencies (although essentially the same communication efficiency may be obtained with smaller antenna sizes when higher conversion efficiency millimeter and ultramicrowave generators are developed); the 8- to 14-micron range of the infrared region appears very promising.
3. To avoid interference with existing terrestrial radio communication links, it would be expedient, in spite of its lower efficiency, to employ the optical maser in the relay of information from space stations back to the earth and between points on the earth's surface (provided there are no clouds, fog, or smoke).

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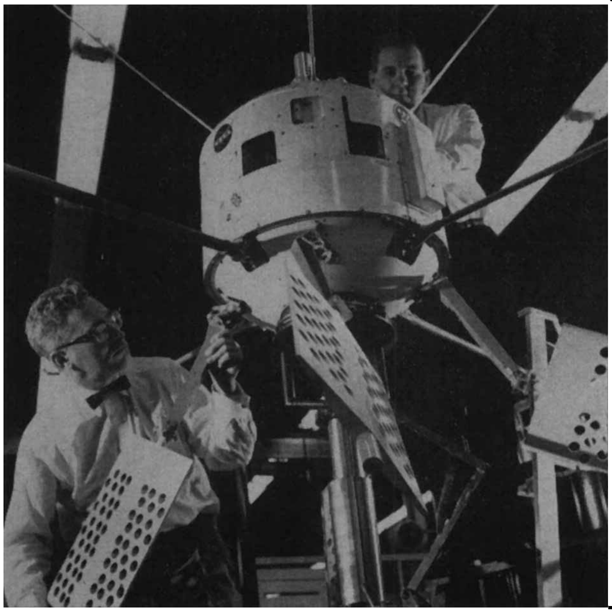

Engineers examine solar paddles and antennas of an engineering test model of the S-52 satellite structure being built at the Westinghouse Electric Corporation's air arm division at Baltimore, Md., for the National Aeronautics and Space Administration. The S-52, a joint United States–United Kingdom project, will measure galactic "noise," or the radio-frequency signals generated by stars and galaxies, the distribution of ozone in the atmosphere, and the quantity and size of micrometeoroids in space. British scientists and engineers will provide the instrumentation for the satellite. Following this model, two prototypes and two flight models will be built before S-52 is launched. The project is managed and technically supervised by NASA's Goddard Space Flight Center, at Greenbelt, Md.