Deep-space optical communications

Recent investigations have shown that laser systems, particularly the incoherent direct detection and transmitted reference systems, have important potential advantages over local heterodyning techniques for achieving effective deep-space communications.

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A major problem in deep-space communication systems is that of obtaining high data rates (of the order of $10^9$ bits per second). This article proposes some design concepts that indicate the probable feasibility of achieving wide-band communications by means of the laser. The example selected here is a hypothetical mission to Venus, chosen because of its great brightness and, hence, high background-noise level. Since no earth satellite relay is assumed, the communication channel includes the atmosphere. The down-link is the one considered because of its high-information-rate requirement.

The primary goals of any space subsystem are generally taken to be low power and low weight. For deep-space, wide-band communication, however, another factor may be equally important—namely, the size of the transmitting aperture. A very large aperture, as would undoubtedly be required by a microwave channel, is likely to prove an obstruction to the sensors of the spacecraft and will, therefore, reduce the time available for collecting information or transmitting it. In this respect, the laser has an important advantage over microwave, as will be seen later.

The magnitude of the deep-space communication problem is shown in Table I. At the August 23–27, 1965, conference at Virginia Polytechnic Institute on "The Exploration of Mars and Venus," the total information required in the early Voyager program was suggested to be of the order of $10^8$ to $10^{18}$ bits. A typical imagery requirement of the geologist interested in rough terrain characteristics of Mars or Venus is 20-cm $\times$ 20-cm photography, by means of which a single picture could contain as many as $10^9$ bits. Based on current capability of the order of 8 bits per second (b/s) of Mariner IV, it could take as long as 11 300 days to transmit $10^{18}$ bits. At the same conference, it was suggested that 1000 b/s may be achieved in time for the early Voyager program. As many as 115 days would be required, even at this data rate. At the 10-Mb/s data rate suggested as a minimum requirement, the transmission time assumes values in seconds.

To increase the information data rate capability significantly at radio frequencies implies consideration of larger antennas in the spacecraft and on the ground, increased power in the spacecraft, and use of higher frequencies (for example, EHF) with the commensurate development requirements and cost to change from the current NASA deep-space instrument facility S-band system. The laser—with its extremely narrow beam due to its short wavelength, notwithstanding its high quantum and background noise—offers the possibility of surpassing RF techniques in its ability to satisfy deep-space requirements. Should it prove superior to RF at data rates of the order of $10^9$ b/s, its growth capability to higher data rates will be much greater than that of RF systems. We can expect the laser communication art to develop in all its component areas, as has been historically achieved in all new technologies.

### I. Space communication problem

<table>
<thead>
<tr>
<th>Early Voyager Requirements, total bits</th>
<th>Transmission Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>at 10 b/s, days</td>
<td>at 100 b/s, days</td>
</tr>
<tr>
<td>at 1000 b/s, days</td>
<td>at 10^3 b/s, seconds</td>
</tr>
<tr>
<td>$10^8$</td>
<td>115</td>
</tr>
<tr>
<td>$10^9$</td>
<td>115</td>
</tr>
</tbody>
</table>

* Approximate requirements for one 20-cm $\times$ 20-cm photo with 15 shades of gray at 10 lines/mm.
**Candidate optical systems**

Three types of systems have been considered:
1. Local heterodyne system (LHS)
2. Direct detection system (DDS)
3. Transmitted reference system (TRS)

Block diagrams of these systems are shown in Fig. 1.

The local heterodyne system often provides the highest signal-to-noise ratio (SNR) of the three systems because the local heterodyne laser can be made sufficiently strong that the shot noise from it dominates all other sources of noise. However, as shall be indicated later, the DDS and TRS can be designed so that the power efficiency is nearly as high as that of the LHS. Moreover, the LHS system suffers from the serious disadvantage of receiver SNR degradation due to spatial dispersive effects of the atmosphere.

For LHS to operate properly, the local laser radiation should maintain spatial coherence with the received signal light over the whole receiving optical aperture. The atmosphere disperses the signal beam so that coherence is lost for much of the time except for very small apertures. For example, based on an atmospheric transmission experiment by Goldstein et al. from noon to midnight over a 4-km path at a wavelength of 0.63 μm, a 3-cm dish would experience 70 percent of the time a loss of at least 15 dB greater than that experienced under atmospheric conditions that permit perfect coherence. During the experiment reception was found to be generally poor except shortly after sunset. Smaller losses may be expected for installations on high mountains and with longer wavelengths, but the prospects are not promising for maintaining reliably the spatial coherence across the aperture needed for an LHS. Another alternative for the LHS is to have a receiver system that consists of a large number of small diffraction-limited dishes. The randomness of the phases of the signals from each dish would then be compensated for by some adaptive scheme that adds the signals in phase.

LHS suffers from one other problem. The local laser must be maintained accurately at a specified frequency difference from that of the received signal light, and thus it is necessary that the local laser be continuously corrected for the Doppler shift. For some missions, the Doppler shift can be very large, typically well over 10 GHz.

The direct detection system is simply a straightforward transmission and detection system, with a single modulated carrier providing video detection. It has a limitation in the loss of phase information of the carrier. Nevertheless, DDS appears to be the most attractive choice at this time.

The transmitted reference system is a heterodyne system in which the reference is transmitted with the signal from the spacecraft. This technique avoids the Doppler shift problem of LHS, but its SNR is lower than that of either the DDS or LHS. It is lower than that of the DDS principally because only half the power transmitted from the spacecraft is signal power. The successful performance of this system depends on the assumption that the atmosphere will not disperse the very close frequencies of the signal and the reference sufficiently to damage their spatial coherence over the receiver aperture. (The frequency separation is of the order of 0.2–10 GHz.) This system can use almost any form of modulation including phase-shift keying (PSK).

Diffraction-limited optics do not provide increased SNR for the DDS and TRS. Since nondiffraction-limited optics will simply have the effect of producing a focal area larger than the Airy disk, the detector is required to have a larger area. It is, therefore, possible to receive light signals through the atmosphere on extremely large nondiffraction-limited apertures with high efficiency by providing adequate detector area at the focus of the optics. For the greatest accuracy, it is desirable:

1. That the optics do not enlarge the focal area beyond a diameter for which the collection of photons by the detector becomes difficult.
2. That the highest frequency of the modulation carried by the light beam remain coherent over the area...

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**Fig. 1. Optical communication system types.**

A—Direct detection system.  B—Local heterodyne system.  C—Transmitted reference system.
of the detector; that is, the mechanical irregularities should not exceed the equivalent of about 1/10 of the wavelength of the highest modulation frequency.

When it is desired to have photon collectors of very large dimensions, the structural requirements may lead to the use of a number of nondiffraction-limited dishes, each with its own detector system; see Fig. 2. The continuously variable delays are introduced to compensate for the changes in path length with change in direction of the received beam.

The configuration of the several receiving apertures must be such that they will not interfere with one another in the directions of interest and such that the compensating delays can be accurately established. In the simplest configuration, all the dishes are installed on a single, very large structure. If it is sufficiently rigid, the whole structure can be moved normal to the direction of the received beam and compensating delays are not required except to correct for the effects of temperature and mechanical stresses.

**Comparison of the LHS, DDS, and TRS**

In order to compare the performances of the LHS, DDS, and TRS, an analysis was made of the transmitter power required by the three systems for shot-noise-limited conditions. The systems were put on an equal footing for the analysis, by assuming that all three systems have the same parameters—in particular, the same transmitter frequency and area, the same total receiver background noise, and the same detector efficiency. Multiple-dish receiver systems are assumed, with the total receiving area (not necessarily the number of dishes) the same for the systems. For the LHS, it was also assumed that the atmosphere does not degrade the coherence of the incoming field. Equivalently, it was assumed that the spatial incoherence of the received signal is compensated for by an adaptive technique for adding in phase the signals from the various dishes. For the TRS the signals from the outputs of the detectors are added in phase, whereas for the DDS they are added linearly, as indicated in Fig. 2. The pessimistic assumption is made that the background noise is spatially coherent over the total collecting area of the systems. And it is assumed that the background noise radiates from a point source, as would be the case if the background arose from Venus’ albedo.

One finds that for these assumptions on the background noise the performances of all three systems are dependent on the receiver collecting area and not on the number of dishes involved. This important property applies theoretically to the TRS, LHS, and DDS systems, regardless of the output SNR per dish. Let

\[
P_{\text{LHS}} = \text{transmitted power required for the LHS}
\]

\[
P_{\text{DDS}} = \text{transmitted power required for the DDS}
\]

\[
P_{\text{TRS}} = \text{transmitted power required for the TRS}
\]

\[
N_b = \text{background noise received by each dish (after optical filtering), photons per second}
\]

\[
M = \text{number of dishes}
\]

\[
N_{bT} = \text{total background noise received by the } M \text{ dishes (after optical filtering), photons per second}
\]

\[
B_T = \text{signal bandwidth}
\]

\[
\alpha = \text{quantum efficiency of the receiver}
\]

\[
X_{SN} = \text{power SNR at output of receiver sum point}
\]

\[
X_{bT} = B_T/\alpha N_{bT} = B_T/\alpha MN_b
\]

\[
= \text{power SNR at output of receiver sum point, if there were collected by the receiver antenna complex one photoelectron per hertz of transmitted signal bandwidth.}
\]

Figures 3 and 4 give plots of \(P_{\text{DDS}}/P_{\text{LHS}}\) and \(P_{\text{TRS}}/2P_{\text{LHS}}\) versus \(X_{bT}\) for \(X_{SN} = 10\). It is noted that the curves are independent of \(M\) in accordance with the results already given above. The curves indicate that for high \(X_{bT}\), the incoherent DDS has a power efficiency as high as that of the LHS. The TRS requires four times as much power as the LHS for high values of \(X_{bT}\) because half the transmitter power is in the information-carrying part of the signal, which results in a fourfold decrease in the power SNR after detection. By proper design of the system (that is, by the use of a wide bandwidth for the signal when necessary and a narrow-band optical filter and small field of view, the quantity \(X_{bT}\) can be made large.

It is found that one generally can achieve, or come close to achieving, shot-noise-limited conditions for the DDS and TRS. A sufficient condition for the DDS and TRS to be shot-noise limited is that

\[
\frac{B_T}{B} \frac{1}{X_{bT}} \approx \alpha N_{bT} \ll 1
\]

This condition is met for the systems in Table II that utilize photomultiplier detectors (Systems 1, 4, and 5).
For all systems $aN_{IS}/B_r \leq 0.1$. It is important to point out, however, that if the systems are partially or completely limited by classical background noise (instead of shot noise), the power performance of the systems is even closer than is indicated in Figs. 3 and 4. The systems become classical background-noise limited when the direction of inequality is reversed in the above equation. Using the results of Fig. 3 one finds that when

$$\frac{1}{X_{SN}} = \frac{N_{IS}}{B_r} \leq 2$$

and $X_{SN} = 10$, the DDS will require less than 1 dB more transmitter power than an equivalent diffraction-limited LHS if the DDS is limited by shot or background noise instead of detector- or receiver-generated noise. These conditions are met for the GaAs DDS using a photomultiplier detector. Moreover, it is found that this DDS requires the same power as the comparable LHS.

So far in the foregoing discussion the comparison has been on the basis that the three systems are operating at the same frequency with no concern being given to the number of receiver dishes required by each system. Now a comparison is made for different frequencies of operation. Table III gives a comparison of the DDS and the LHS, both operating at 0.84 $\mu$m and 10 $\mu$m. In the derivation of the table, it was assumed that the systems are signal shot-noise limited with $X_{SN}$ large so the DDS has as high a power efficiency as the LHS. To put the systems on the same basis for comparison, they were specified this time to have the same transmitter power, the same receiving area, and the same detector efficiency.

The DDS is assumed to have the same receiver dish configuration as specified for the Venus mission given in Table II; that is, it consists of 25 ten-meter dishes. The assumption is again made that the degrading effects of the atmosphere can be ignored for the LHS.

What was allowed to vary for the systems and serve as a parameter for comparison is the transmitter dish diameter. The transmitter dish diameters were set so as to give the same receiver SNR in all the systems. Also used as a basis of comparison is the number of receiver dishes required for the systems. The sizes of the transmitter dishes required are given in Table III in terms of the dish diameter $D_{TR}$ required for the LHS operated at 0.84 $\mu$m. It can be seen that at 0.84 $\mu$m the transmitter dish needed for the DDS is the same as for the LHS and hence, on this basis, the systems are equivalent. However, when the systems are compared on the basis of the number of dishes required, this is not the case. In particular, the LHS requires 2.8 million dishes if one uses a dish size of 3 cm in order to attempt to eliminate atmospheric degradation. This is in contrast to requiring only 25 dishes for the DDS system. As was noted previously, the dish size of 3 cm actually is too large, providing serious degradation a large percentage of the time. Hence, the performance of the LHS will actually be worse than indicated.

**II. Mission to Venus**

<table>
<thead>
<tr>
<th>System Number</th>
<th>Laser</th>
<th>Detector</th>
<th>Transmitter Aperture Diameter, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GaAs</td>
<td>S-1 photo-multiplier</td>
<td>DSS</td>
</tr>
<tr>
<td>2</td>
<td>GaAs</td>
<td>Diode</td>
<td>29</td>
</tr>
<tr>
<td>3</td>
<td>GaAs</td>
<td>Avalanche diode</td>
<td>56</td>
</tr>
<tr>
<td>4</td>
<td>Diode</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Argon II</td>
<td>S-20 photo-multiplier</td>
<td>3.5</td>
</tr>
<tr>
<td>6</td>
<td>N$_2$CO$_2$</td>
<td>Cu-doped germanium</td>
<td>78</td>
</tr>
<tr>
<td>7</td>
<td>N$_2$CO$_2$</td>
<td>Ideal (not available)</td>
<td>30000</td>
</tr>
<tr>
<td>8</td>
<td>Ho-doped YAG</td>
<td>Ideal (not available)</td>
<td>125</td>
</tr>
</tbody>
</table>

Microwave S-band system: diameter = 2000 cm

Notes:
Distance = 180 million km
Power input to transmitter = 30 watts
Information rate = 10$^8$ b/s
Error rate = 10$^{-4}$
Laser receiver: 25 apertures, each 10 meters in diameter
Microwave receiver: one paraboloid, 50 meters in diameter
Modulator: PCM/PPM, alphabet size of 32, $B_t = 10^6$ Hz

**III. Comparison of DDS and LHS**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>DDS</th>
<th>LHS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength ($\lambda$), micrometers</td>
<td>0.84</td>
<td>0.84</td>
</tr>
<tr>
<td>Transmitter dish diameter required</td>
<td>10 $D_{TR}$</td>
<td>10 $D_{TR}$</td>
</tr>
<tr>
<td>Receiver dish diameter, meters</td>
<td>0.03</td>
<td>0.3</td>
</tr>
<tr>
<td>Number of receiver dishes (M)</td>
<td>25</td>
<td>2.8 $\times$ 10$^4$</td>
</tr>
</tbody>
</table>

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Table III also indicates that the transmitter dish diameter for the 10-μm system has to be about 3.5 times that for the 0.84-μm system. Use of a CO₂ laser operating at 10 μm for the LHS will offer considerable improvement as far as the number of dishes necessary; however, as the table shows, an excessively large number still can be expected to be required. The spatial correlation distance is approximately proportional to the signal wavelength; hence, for the 10-μm system, a receiver dish diameter of 0.3 meter should be used. The table indicates that for this dish diameter 27 800 dishes are required. Even if one optimistically assumes that a receiver dish diameter of 2 meters can be used, 625 dishes would be needed for the ground complex.

**System analysis**

**Sources of noise.** The four sources of noise in an optical detector are as follows:

1. **Thermal.** Similar to that at microwave frequencies.
2. **Quantum or shot.** Very high compared with that at microwave frequencies. This category includes the shot noise due to the signal photons, the background photons, and the photons that are equivalent to the dark current.
3. **Dark current.** Adds to shot noise. There is no equivalent at microwave frequencies.
4. **Background.** Very high compared with normal operations in the microwave region. The background calculated for the systems listed in Table II was based on an irradiance of 10⁻¹⁰ W/cm²·μm for Venus, and a radiance from the sun-illuminated atmosphere of 1.3 × 10⁻⁴ W/cm²·sr·μm⁻².

**Other atmospheric effects.** Because of the earth’s rotation, at least three ground sites are required. In addition, to minimize the attenuation that may occur due to bad weather, these sites must be selected for their high probability of clear weather. There are such areas on the earth. The probability of clear weather can be further increased by providing redundancy with additional sites. The values used for atmospheric attenuation in the systems listed in Table II are for clear weather.¹

**Transmitter optics.** Spacecraft transmitter optics must be small and light. A laser should be excellent for this purpose. If the beam from it is perfectly coherent, it can in theory be focused to a point of dimension of the order of a few wavelengths of light, so that it is possible to make full use of the collimating capability of diffraction-limited optics. The limitations for achieving this are (1) the degree to which the laser beam is truly coherent and (2) the stability of the laser area.

Gas lasers are currently the best lasers for meeting these two conditions. Semiconductor lasers are at present poor in this respect. Although the gallium arsenide laser may not be steady at present (no measurements are known to have been made to determine the laser area stability), it is expected that it will be when single-mode operation is achieved. It may be necessary, however, to maintain the temperature very constant.

As to the optical mirror, diffraction-limited dishes up to one meter are currently being discussed for deep-space communication transmitters. Such a size appears feasible in view of plans for the Orbiting Astronomical Observatory (OAO) program to orbit a telescope of this diameter. Such large dishes lead to difficult design problems, including an extreme tracking requirement (for example, about 1/8 μrad), which is also planned in the OAO program, and maintaining alignment of optical system elements and diffraction-limited characteristics after withstanding the launch and space environment during a long mission to the planets. These problems increase rapidly with the size of the aperture. It is, therefore, important to minimize the aperture size.

**Optical filter.** An important component of the receiving optics is the optical filter, which is incorporated to reduce the background noise. The bandwidth of the filter will usually be large compared with the modulation bandwidth.

Sharp filters operate on the light interference and are sensitive to the angle of incidence. It is, therefore, important to insure that all the signal light is incident on the filter within its angular field of view, and no background light which is incident at larger angles reaches the detector.

Lyott filters are attractive because they provide a wide field of view with narrow bandwidth. A filter of 0.5 Å (0.05 nm) at a wavelength of 0.84 μm, about 5 cm in diameter and 40 cm long, can be made, using calcite and quartz, with a field of view of 5° (0.1 rad). The filter, which can be tuned through ±0.5 Å, is expected to have a transmissivity of 0.15. It is sensitive to temperature changes, which should be maintained within 0.1°K.

**Transmitter laser choice.** Of the three types of lasers—gas, solid-state, and semiconductor—the most desirable for ultimate development for deep-space communications is the semiconductor type (currently GaAs) because of its small size and weight, its promise of ready capability for wide-band pulsed internal modulation with simple techniques, and its potential for high efficiency (between 0.3 and 0.6) at reasonable temperatures.

In the visible region, gas lasers having a single mode, very narrow bandwidth, and high power can be made; however, the efficiency is low—about 0.1 percent or less for the narrow-band, single-mode operation. In the far-infrared region, molecular gas lasers have recently appeared. The N₂-CO₂ laser (λ = 10.55 μm), which is receiving much attention at present, has been made with an efficiency of about 10 percent. This wavelength falls within a wide atmospheric window. However, compared with GaAs, it has the following disadvantages:

1. It is not possible to obtain high data rate and very narrow pulsed operation. At present, fundamental limitations rule out wide-band internal modulation.
2. For a given diameter of the diffraction-limited dish in the spacecraft, the gain is −22 dB relative to GaAs (because of longer wavelength).

It remains also to develop wide-band detectors that are not detector-noise limited for the direct detection and transmitted reference system. The transmissivity of the atmosphere is about the same in clear weather as at a 0.84-μm/wavelength. Although the N₂-CO₂ laser will operate satisfactorily in worse weather conditions than the GaAs laser will, there are weather conditions in which neither laser can operate.

Solid-state lasers, such as ruby, that radiate in the visible region have low power efficiencies (less than 1 percent) and are useful mainly for high-peak power pulses at low repetition rates. A holmium-doped yttrium aluminum garnet (YAG) laser has been made to lase CW in the infrared region at 2.3 μm with a power efficiency of 5 percent at liquid nitrogen temperatures (77°K); a
realizable efficiency of 10 percent seems reasonable. Outputs of the order of a few watts were achieved, with much higher outputs being anticipated. As in the case of N₂CO₃, there is the problem of developing an efficient modulator for obtaining narrow (nanosecond) pulses at a high data rate of the type desired. High-efficiency pulsed operation with higher repetition rates than tens of kilohertz appears unfeasible because of the lack of a flash lamp that can operate at these higher rates. Also, there remains the equally important problem of developing a good detector for receiver systems that do not use local heterodyning.

Semiconductor lasers (for example, GaAs at 0.84 μm) are at present the most promising, but require considerable development before they can be effectively used for deep-space communication. The present problems with GaAs lasers are concerned with

1. **Multimode operation.** The fluorescence bandwidth is very large, about 200 Å wide; most of the power is within a band of about 20 Å (860 GHz). It comprises a large number of equispaced lines, each about 10 MHz wide. After single-mode operation is achieved, the type of modulation selected must, therefore, be able to operate with a carrier having this bandwidth.

2. **Stability.** The lasing area may shift in position when it is internally modulated. The lasing area must be extremely stable if we are to make full use of the gain capability of the diffraction-limited optics at the transmitter.

3. **Power.** Continuous-wave power of the order of 10 watts requires operation at 4°K; a temperature difficult to reach in a spacecraft. However, it is expected that temperatures of 77°K might be achieved in a spacecraft and that the GaAs laser can be developed to powers in excess of 10 watts at such temperatures or higher. One-watt CW power has been achieved to date at 77°K. It is anticipated that solving the first two problems will permit optical collimation down to a narrow beam.

Although gas lasers currently have the desirable characteristics that the semiconductor laser has yet to achieve (single-mode operation with spatially coherent, stable output), future developments in the problem areas just mentioned may lead to the choice of a semiconductor laser type for deep-space communications.

**Coding and modulation.** Table IV is based on Gaussian noise statistics that apply to microwave communications. With the quantum nature of light and the unknown statistics of atmospheric effects, comparable figures for optical communication must still be derived. However, the relative order of magnitude of the required SNR per bit for each type shown is expected to hold for optical communications.

An optical beam can be modulated in phase, amplitude, and polarization. The last has some valuable characteristics. The relative merits of these are not discussed herein. The modulation type selected to compare the systems listed in Table II is PCM/PPM with an alphabet size of 32 (PCM-32 orthogonal). A PCM system of larger alphabet is not used because of the complexities involved. Sequential decoding is not chosen because it is not economically feasible for high data rates. Moreover, the small bit-error rates (of the order of 10⁻⁴ or less) that can be achieved by using sophisticated codes is not necessary for the high-data-rate video picture communication. Bit-error probability of the order of 10⁻³ or 10⁻² can produce pictures of satisfactory quality. Of course, engineering data, which would be transmitted at a lower data rate than video data (a rate of 10³ b/s as compared with 10⁶ b/s), need a bit-error probability of about 10⁻⁵ and hence require error-correcting codes. In Table II, the conservative bit-error probability of 10⁻⁴ was used for comparison purposes for the high data rate transmission.

**Detectors.** Photodetectors are in effect photon-to-electron converters. In the course of conversion, they provide gain and noise in varying degrees. With the weak light intensity of deep-space communication, the possibility of gain in the photodetector is of prime importance to minimize the effect of thermal noise generated in the output resistor. Two detectors are of special interest in this respect. The first, the photomultiplier, is excellent because of its high gain (of the order of 10⁴) with little generation of noise; however, it has only a fair quantum efficiency, which rapidly becomes poor beyond a wavelength of about 0.7 μm. The second detector of interest is the microplasma free avalanche diode, recently developed by Bell Telephone Laboratories.²⁴

In an avalanche diode recently tested, the shot noise is proportional to the cube of the current gain of the de-
ector, whereas the signal is proportional to the square of the gain; see Fig. 5. The ordinate distance between the signal and noise curves is the SNR. It is clear that the smaller the gain, the greater the SNR down to the point where the constant noise—that is, the thermal noise—takes over. For maximum SNR, therefore, the gain should be adjusted so that the shot noise is approximately equal to the thermal noise, and the thermal noise should be kept to a minimum by cooling.

The characteristics obtained to date and predicted on the silicon diode for 0.75 μm (gallium arsenide phos-
phide laser) are:
1. The shot noise increases as \( G^2 \), where \( m \) generally lies between 2.5 and 3.0. To date the figure is 3.0. This figure will probably be reduced.
2. Gain–bandwidth product is \( 10^{11} \). It is not likely to be increased materially, possibly up to \( 2 \times 10^{13} \).
3. Avalanche operation is stable.
4. The sensitive area is very small, about 0.005 cm in diameter.
5. Quantum efficiency is high, over 0.5.
6. Dark current between \( 10^{-10} \) and \( 10^{-11} \) ampere at room temperature. It varies with the gain.

The germanium diode has similar avalanche characteristics at 0.84 μm. At room temperature, however, its dark current noise is too high, although at low temperatures it is likely to be acceptably low.

**Laser-detector combination**

At this stage of laser and detector development, there is no combination that could be said to be unquestionably superior to microwave. In broad summary, one can say:
1. He-Ne and argon gas lasers are too inefficient.
2. Although the molecular gas lasers have the advantage of reasonably high efficiency, they have a number of disadvantages that must be overcome if they are to be used most effectively for deep-space high-data-rate links. For one thing, it is not possible at present to obtain very wide-band pulse modulation (for example, pulse widths of the order of nanoseconds for a PCM incoherent direct-detection communication link). Also, it is necessary to develop exceptionally good detectors.
Finally, the long wavelength has the disadvantage of requiring a larger transmitter aperture, all other things being equal.

3. Solid-state lasers in the visible region are not efficient and operate at low repetition rates. Holmium-doped YAG in the infrared region has a high efficiency but requires the development of efficient wide-band pulsed modulators and detectors for systems that do not use local heterodyning. In addition, it requires cooling to 77°C.

4. Semiconductors are most desirable because of their efficiency, size, weight, and potential ease of modulation; however, the most efficient to date, GaAs, operating in the near infrared, suffers from multimode and possibly spatial instability and, as yet, only one watt has been achieved at 77°C. Developed detectors at this wavelength (photomultipliers having poor quantum efficiency and diodes with too small gains) are of only fair quality.

**Size of optics**

It is believed that an important criterion of the acceptability of a system will be the size of the aperture in the spacecraft, to minimize obstruction to view. In this respect, the laser appears far superior to other communication systems. For laser operation, small optics in the spacecraft are desirable also for four other reasons:
1. Simpler pointing and tracking equipment.
2. Reduced sensitivity to vibration and distortion due to temperature gradients.
3. Simpler optics in the spacecraft for illuminating the diffraction-limited mirror with the laser.

**Quantitative comparison of the DDS and TRS**

In order to compare possible future systems, a specific communications mission to Venus was considered. Its principal components are listed in Table II. The criterion for the comparison of the several systems shown is the diameter of a diffraction-limited dish in the spacecraft that will provide the communication performance specified for an input power of 30 watts to the laser or microwave transmitter. PCM/PPM with an alphabet size of 32 was chosen, as indicated previously. The results listed below were calculated from the quantities shown in the Appendix and in Table V. Analysis of Table V shows that maximizing the ratio of the transmitted bandwidth to the information bandwidth significantly affects the system SNR. For the system examples presented,

### V. Expressions for output signal and noise

<table>
<thead>
<tr>
<th>Signal Noise</th>
<th>DDS</th>
<th>LHS</th>
<th>TRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Shot</td>
<td>( a^2q^2G^2R\alpha_N^3 )</td>
<td>( kTB_T )</td>
<td>( 2aq^2G^2R\alpha_N\beta_B )</td>
</tr>
<tr>
<td>Background</td>
<td>( 2aq^2G^2R\alpha_N(\alpha_N + \beta_B) )</td>
<td>( 2aq^2G^2R\alpha_N\beta_B^T )</td>
<td>( 2aq^2G^2R\alpha_N\beta_B )</td>
</tr>
</tbody>
</table>

### Noise-signal

| Thermal | \( 5.4 \times 10^{14} \) | \( 5.4 \times 10^{14} \) | \( 5.4 \times 10^{14} \) |
| Shot | \( 2G^2\alpha_N^3 \) | \( 2G^2\alpha_N\beta_B \) | \( 2G^2\alpha_N\beta_B \) |
| Background | \( N_0(\alpha_N + \beta_B) \) | \( N_0\beta_B \) | \( N_0\beta_B \) |

Notes:
1. \( N_0 = \beta_B/\beta_B \)
2. \( N_0 = \beta_B \)
3. \( m = 2 \), except for avalanche diode, where \( 2.5 < m < 5 \). Chosen as 3 in calculations.
a 0.1-GHz bandwidth for pulses of the order of 10 ns was chosen for the PPM. It should be recognized that such a high modulation bandwidth may be difficult to achieve because of modulator limitations, and even if achieved it may reduce the efficiency of the laser.

The following comments refer to the DDS listed in Table II.

1. The GaAs laser with S-1 photomultiplier is attractive despite the low quantum efficiency of the S-1 phosphor. In view of the high gain possible with the photomultiplier, the thermal noise is small relative to shot noise.

2. The GaAs laser with diode detector is worse than System 1, because the gain is unity and thus the thermal noise becomes dominant. The quantum efficiency of 0.5 is excellent.

3. In the case of the GaAs laser with an avalanche diode detector, the results in the table indicate that at 0.84-μm wavelength, this detector gives efficiencies as great as the photomultiplier detector.

4. The use of a semiconductor laser in the visible region, with an S-20 photomultiplier detector, shows excellent performance potential; however, there are no signs at this time of the possibility of developing a high-power semiconductor laser in the visible part of the spectrum.

5. The argon laser with an S-20 photomultiplier is a bit poorer than System 1 because of the very low efficiency of its laser.

6. The N₂CO₃ system with Cu-doped germanium is poor, because it is detector-noise limited.

7. When N₂CO₃ is used with an ideal detector, the results indicate a high loss imposed by the longer wavelength, which would occur even if a good detector were developed.

8. The Ho-doped YAG system may be fairly attractive if the postulated detector (for which a quantum efficiency of 0.3 was assumed in deriving the table) can be developed.

The comments on the first five of these systems apply to TRS as well. In every case, except for the DDS using the thermal-noise-limited diode detector, TRS is worse than DDS, largely because only half the laser power is transmitted as the signal.

The microwave system was calculated for the S-band region (λ = 10 cm) for a single receiver dish 50 meters in diameter (equal in area to the 25 dishes, each 10 meters in diameter, assumed for laser communication).

Appendix. Symbols and quantities of basic configurations for mission to Venus

1. Bₚ, information bandwidth and information rate = 10⁶ Hz.

2. Bₛ, transmission bandwidth = 10⁷ Hz.

3. Bₒ, optical filter bandwidth, Hz; 0.015/λ² for 0.5 A filter.

4. Dₒ, diameter of one ground dish, 10 meters. There are 25 such dishes. The angle of view of each is 0.2 mrad, so that effect of radiance of atmosphere is small compared to that of Venus.

5. Dₛ, diameter of spacecraft dish.

6. Error rate = 10⁻⁴.

7. G, gain in detector: 10⁴ for photomultiplier; 1 for diode; for avalanche, calculate for condition of shot noise = thermal noise.

8. Hₛ, irradiance of Venus = 10⁻¹⁰ W/cm²·μm; Hₑ, irradiance of sunlit atmosphere = 1.3 × 10⁻¹⁴ W/cm²·sr·μm.

9. lₑ, optical transmissivity; lₒ for whole system, 0.05; lₛ for transmitter, 0.5; lₑ for atmosphere, 0.7; lₒ for receiver, 0.15 (includes optical filter).

10. Nₛ, number of effective photons incident per second on the detector; Nₒ for signal, Nₑ for heterodyne reference, Nₚ for background, Nₑ for equivalent dark current (negligible in systems of Table II).

11. m, exponent of G for shot effect; equals 2 except for avalanche diode when it is between 2.5 and 3.

12. Pₑ, power of laser radiation, watts; Pₛ = power incident in detector, Pₒ = background power on detector.

13. Rₒ, range = 1.8 × 10⁸ km (10⁴ nmi).

14. Rₛ, output impedance = 50 ohms.

15. T, temperature of output impedance = 20²K.

16. α, quantum efficiency = 3.6 × 10⁻⁵ for System 1, 0.5 for diodes, 0.18 for Systems 4 and 5.

17. λ, light wavelength = 0.48 × 10⁻⁴ cm for argon.

18. h, Planck's constant = 6.62 × 10⁻¹² J·s.

19. k, Boltzmann's constant = 1.38 × 10⁻²³ J/²K.

20. q, electron charge = 1.6 × 10⁻¹⁹ coulomb.

21. The SNR required for PCM/PPM with an alphabet size of 32 for laser communication is 10.

22. Range equation:

\[ Pₛ = \left( \frac{\pi^2 Dₛ^2 Dₑ^2 \gamma_k Pₑ}{\lambda^2 Rₚ^2} \right)^{\frac{1}{4}} \]

23. Pₛ = \frac{3 × 10^{10}}{\frac{\lambda}{\lambda}} hN

24. Effective signal power at receiver = Pₛ \frac{Bₛ}{B_r} n

25. Efficiency of microwave antennas = 0.7, of microwave transmitter = 0.33, of semiconductor lasers = 0.33, of argon laser = 0.0005, of N₂CO₃ laser = 0.1, of Ho-doped YAG = 0.1.


REFERENCES


