Performance of Single- and Multiple-Dish Laser Communications Systems

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PERFORMANCE OF SINGLE- AND MULTIPLE-DISH LASER COMMUNICATIONS SYSTEMS

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Abstract

A comparison is given of three potentially useful types of laser communications systems. These are the incoherent direct detection systems (DDS), the transmitted reference system (TRS) and the coherent local heterodyning system (LHS). Both single- and multiple-dish receiver systems are considered. In all cases a photomultiplier receiver detector is assumed.

In the analysis the wave interference noise (or equivalently, classical noise) has been taken into account. The results are given for the case where the background noise arises from a point source, from many point sources or from a uniformly radiating background. Also, the case where the receiving aperture is not diffraction limited, is considered. Convenient curves are given which permit one to determine the performance of the three systems for various background conditions and system parameters.

It is pointed out that the transmitter power required for a communications system using a multiple-dish receiver complex does not decrease always in direct proportion to the reciprocal of the increase in the number of receiver dishes used. Curves are given showing the receiver collecting aperture loss as a function of the number of collecting apertures.

The results are applied to various postulated direct detection and transmitted reference systems for deep space Venus missions. Space-to-ground links are considered only for the case where the communications channel includes the atmosphere of the earth. It is indicated that for the postulated systems of interest, one is always short noise limited even during the daytime operating conditions. The various systems are compared to each other and to microwave systems. When all other system parameters are made equal, a 3 GHz S-band and 25 GHz Ka-band microwave systems are found to require transmitter aperture diameters of 2,000 cm and 1,000 cm, respectively; a GaAs DDS needs a 64 cm diameter aperture if an S-1 surface photomultiplier detector is used; and an Argon II DDS requires a 208 cm transmitter diameter.

Summary

1. System Performance

In the literature, considerable work has been carried out on optical communications and radar systems such as the coherent local heterodyning system (LHS) and the incoherent direct detection system (DDS); see references (1), (2), (3) and (4), for example. Much of the work was carried out neglecting the wave interference noise (or equivalently, the classical noise). When the wave interference noise was included, a quantum analysis was used and only the noise alone case was considered. Also, usually the receiver dish was assumed to be diffraction limited. In this work a simple semiclassical analysis was used to attain the performances, with the interference noise included, of various types of laser communication systems. The results are given for when the background noise originates from a point source, from many point sources and from a uniformly radiating background. Furthermore, the results are given for nondiffraction limited receiving dishes as well as for diffraction limited receiving apertures.

The three types of systems considered are the:
1. Local Heterodyning System
2. Direct Detection System
3. Transmitted Reference System (TRS)

The LHS is the optical equivalent of the microwave superheterodyning receiver system. The direct detection system is simply a straightforward transmission and detection system, with a single modulated carrier providing video detection. The transmitted reference system is a heterodyne system in which the reference is transmitted with the signal from the spacecraft; further details on this system are given in Reference 6.

For deep-space communication systems it is necessary to employ a large receiver collection area in order to reduce the complexity, size and power requirements for the spacecraft transmitter. To achieve a large collecting aperture a multiple-dish receiver system becomes an economical necessity beyond a certain receiver collecting area and hence the interest in multiple-dish receiver systems.

Figures 1, 2 and 3 give the performance characteristics of single- and multiple-dish systems for the LHS, TRS, and DDS. A photomultiplier receiver detector was assumed. In the figures

\[ X_d = \text{power SNR at the output of receiver sum point if there were collected} \]
by the receiver and antenna complex one
photoelectron per second per hertz of
transmitted signal bandwidth = $B_T / \alpha MN_B$

$\alpha$ = quantum efficiency of the receiver
detector

$B_T$ = signal bandwidth, Hz

$M$ = number of receiver dishes

$N_B$ = background noise received by each
dish within its field of view after
optical filtering, photons per second

$X_{SN}$ = power SNR at output of receiver sum
point

$n_{LH}$ = number of photoelectrons per second
per hertz of signal bandwidth re-
cquired at detector surface in order
to obtain a SNR of $X_{SN}$ at the re-
civer sum point for the LHS

$n_{DD}$ = same definition as for $n_{LH}$ for DDS a
and TRS.

(Note: for a pulsed modulation, such
as pulse position modulation, $n_{DD}$
and $n_{TR}$ each represent the number
of photoelectrons received per
second per hertz of signal bandwidth
during the pulse on time. In the
case of a CW transmission which uses
frequency or phase modulation $n_{LH}$
$n_{TR}$ each represent the average number
of photoelectrons received per-
second per hertz of signal bandwidth.)

$H$ = number of real, or equivalent,
spatially independent background
noise sources.

$B_0$ = optical filter bandwidth, Hz.

The results given in the figures apply for
diffraction and nondiffraction limited receiver
systems and for multiple-dish as well as single-
dish systems.

For nondiffraction limited dishes the shot
noise is determined as for a diffraction limited
dish by the total number of signal and noise
photons received per second. However, for a non-
diffraction limited dish the ratio of the clas-
ical background noise or wave-interference
noise to the shot noise is reduced relative to
what it is for a diffraction limited dish re-
civer system. For a receiver having non-
diffraction limited optics the classical
background noise resulting from the mixing
of the background noise frequency com-
ponents with the signal frequency components is
equal to approximately the level it would be if
the receiver dish were diffraction limited and
directed so as to receive the signal. At the
same time the component of the shot noise due to
the background noise will be greater than what
it would be if the receiver dish were diffraction
limited by the increase in the receiver
field of view. The classical background noise
resulting from the mixing of the background
noise frequency components with itself is
reduced relative to the shot noise level by a
factor equal to the number of spatially
independent background noise sources in
the receiver field of view which are also
statistically independent. Two noise sources
are spatially independent if they are separated
by an amount equal to or greater than the re-
civer diffraction limited beamwidth, i.e.,
the beam width the receiver dish would have
if it were diffraction limited. The number
of spatially independent noise sources is
designated as $H$. If the background noise is
uniform over the receiver field of view, the
classical background noise resulting from the
mixing of the signal with the background
noise would also be reduced by the factor $H$.

The results given in Figure 1 through
3 apply for a multiple M-dish system in
which all the dishes have the same collecting
area, the same field of view, all the re-
civers observe the same background noise, and
where the wave-interference noise terms due
to the mixing of the signal with the back-
ground noise is reduced by the factor $H$. The
results of these figures can, however, be
applied to a more general multiple-dish sys-
tem for it was found that a multiple-dish
system has the same performance as a single-
dish system having the same total collecting
area when the fields of view of the component
dishes of the many-dish system are equal to
each other and to the field of view of the
single-dish receiver such that the dishes see
the same background noise.

The dashed curve in Figures 1 through
3 (as well as in Figures 4 through 7 to follow)
indicate the points at which the classical
background noise equals the shot noise. Thus
the dashed curves represent the boundary be-
tween the shot noise limited region and clas-
sical background noise limited region for the
system. The $D = B_0 / H B_0 = 0$ curve corresponds
to completely shot noise limited conditions.
For practical laser communication systems
one finds that one is effectively completely
shot noise limited.

For shot noise limited conditions one
can use the following simple expressions
for evaluating system performance:

$X_{SN} = n_{LH}$ for the LHS (1)

$X_{SN} = \frac{n_{TR}}{4(1+ \frac{1}{n_{TR}} X^2_B)}$ for the TRS (1a)

$X_{SN} = \frac{n_{DD}}{2(1+ \frac{1}{n_{DD}} X^2_B)}$ for the DDS (1b)

When the background noise is zero, or small
enough (that is, $X_B = 0$, or is small enough) one has the following results:

$n_{LH} = X_{SN} X_B$ (2)
\[ n_{\text{TR}} = 4 X_{\text{SN}} \quad (2a) \]
\[ n_{\text{DD}} = 2 X_{\text{SN}} \quad (2b) \]

Using (1a) and (1b) one finds that (2a) and (2b) hold when
\[ \frac{1}{X_{\text{b}}} = \frac{X_{\text{SN}}}{2} \quad (3) \]

Hence when condition (3) hold the following two statements are true:

1. The TRS requires four times as much power as an equivalent LHS in order to achieve the same receiver power signal-to-noise ratio.

2. The DDS requires only twice as much power as an equivalent LHS in order to achieve the same receiver power signal-to-noise ratio.

Hence, based on the above results, it follows that when condition (3) holds the simple noncoherent DDS requires only 3 dB more power than the optimum coherent LHS in order that the receiver signal-to-noise ratios for the two systems be identical. These results assumed that there is no atmospheric loss for the LHS. A postulated GaAs DDS was found to be within 0.1 dB of the optimum performance specified by (2b) (See Table 1.)

Figure 4, 5, 6, and 7 give a comparison of the DDS and TRS performance relative to the LHS. Figures 4 and 5 show plots of the ratio \( n_{\text{TR}}/n_{\text{LHS}} \) and \( n_{\text{DD}}/n_{\text{LHS}} \) for \( X_{\text{SN}} = 10 \). Figures 6 and 7 show similar curves of \( n_{\text{TR}}/n_{\text{LHS}} \) for \( X_{\text{SN}} = 3 \) and 50. The results of Figures 4 through 7 indicate that for a fixed \( B_0 \) and \( X_b \), the larger \( B_T \) is the closer in power-wise are the DDS and TRS to the LHS. This indicated dependency is more pronounced when the inequality of (3) is reversed. Moreover, when \( B_T = B_0 \) the performance of the DDS and TRS relative to the LHS is essentially the same for all background noise conditions.

It should be noted that the comparisons of the performances of the TRS and DDS with respect to the LHS in terms of \( n_{\text{LHS}} \), \( n_{\text{TR}} \) and \( n_{\text{DD}} \) as given by the curves of Figures 4 through 7 are not exact comparisons. In deriving these curves it was assumed that the systems are equivalent if their power signal-to-noise ratios are equal. This would be true if the statistics of the signal and noise at the receiver output were identical for all three systems, which they are not. The curves given in Figures 4 through 7 show that as \( B_T = B_0 \), the performance of the DDS and TRS relative to the LHS is essentially the same for all background noise conditions.

In contrast to microwave communication system it is found that for the DDS and TRS laser communication systems the transmitter power required does not decrease in direct proportion to the reciprocal of the increase in the receiver collector area. For the DDS and TRS this inverse first power relationship will hold up to a high enough background level. At this point and beyond it is as if the receiver collecting aperture area were less than the true aperture area. One may speak of a receiver collecting aperture loss, \( L \), which represents the amount by which the transmitter power has to be increased above that which would be required if the transmitter power were indeed inversely proportional to the collecting area. One finds that, the inverse first power relationship will hold for the DDS and TRS as long as the background noise is small such that (2a) and (2b) hold, or equivalently, as long as inequality (3) holds. The quantity \( L \) also represents the increase in transmitter power required, for a given receiver system above that required if the background noise were negligible.

It is found that for a large enough receiver aperture or background noise such that
\[ \sqrt{\frac{2}{X_{\text{b}}}} \gg \sqrt{X_{\text{SN}}} \quad (4) \]
where \( X_{\text{SN}} \) is the required receiver power signal-to-noise ratio, \( L \) is given by the following approximate expression for the DDS
\[ L = \frac{1}{\sqrt{2 X_{\text{b}} X_{\text{SN}}}} \quad (5) \]
(Note that (4) is approximately (3) with the direction of the inequality reversed.) For the case were the receiver field of view is fixed as the collecting aperture area increases one finds that
\[ L \equiv \sqrt{K} \quad (6) \]
where \( K \) is the factor by which the dish area is increased, \( X_b \) being directly proportional to the reciprocal of the dish area in this case.

Figure 8 gives a plot of the receiver collecting aperture loss as a function of \( X_b \) for the DDS. The curve shows that as long as \( X_b < 0.13 \) the collecting aperture loss is less than 1 dB.

Figure 9 gives a plot for the DDS of \( L_K \) as a function of \( X_b \), where \( L_K \) is the increase in the collecting aperture loss, \( L \), as a result of an increase in the aperture area or the number of receiver dishes by a factor \( K \) for the assumption that the receiver field of view remains fixed in the case of a single dish system. In Figure 9 the value of \( X_b \) used for the abscissa is the value of \( X_b \) for the system prior to the
increase of the collecting aperture by the factor $K$.

An interesting relationship results from (5). It is the fact that for a given background noise level, collecting dish aperture area and field of view, the receiver collecting aperture loss decreases with increasing signal bandwidth when (4) holds. Specifically, the required transmitter power goes down as one over the square root of the signal bandwidth, i.e.,

$$P_{DD} \propto \frac{1}{\sqrt{B_T}}$$  \hspace{1cm} (7)

Hence when a pulse position modulation is used, the narrowest possible pulse width should be used as long as (4) holds.

2.0 Quantitive Comparison of the DDS and TRS for Deep Space Communications

Using the above results a comparison was made between various laser systems for deep space communications from a space vehicle to a ground terminal. The communication link involves propagation through the atmosphere. Consideration is given only to the DDS and TRS because of the disadvantages imposed by the atmosphere on an LHS system as indicated in reference 5. The laser systems were also compared to a 3 GHz S-band and 35 GHz Ka-Band microwave systems. For the purpose of the comparison a Venus mission was assumed. What was used as a basis for the comparison of the various systems was the diameter of the transmitter dish required in the spacecraft with all other basic system parameters being equal. The prime power available to the laser and microwave transmitter systems were all set equal to 30 watts; all systems were assumed to have the same aperture collecting area for the receiver complex; it consisting of 25 10-meter dishes for the laser systems and one 50 meter dish for the microwave system; the field of view for each of the receiver dishes was assumed to be 0.2 mrad; the modulation assumed for all systems was pulse position modulation (PPM) with an alphabet size of 32; the information rate was assumed to be 10^7 bits/secs. and the bit error rate 10^-4. The spacecraft was assumed to be in front of Venus so that the background noise includes Venus radiation. For the examples chosen daylight operation was assumed so that the background noise also includes sunlight scattering. In order to achieve the desired data rate for the modulation chosen the signal bandwidth has to be at least 100 MHz, or equivalently, the pulse width has to be 10 nanoseconds. Some of the other laser and microwave system parameters assumed for the comparison are indicated in Table I.

For the assumptions given all the systems considered were shot noise limited. One gets an idea of the order of magnitude of the degree to which the systems are shot noise limited by considering the magnitude of the wave interference noise for the case of the CO$_2$ system, the wave interference noise being largest relative to the shot noise for the CO$_2$ system. With this system the background noise is primarily due to the sunlight scattering, Venus radiation being negligible. It is found that for the CO$_2$ system $H = 2 \times 10^6$ and $B_T/B_0 \approx 2 \times 10^{-4}$. Equivalently, the ratio of the wave-interference noise to the shot noise is of the order of $2 \times 10^{-4}$.

Of the systems presented, the one that appears most promising is the GaAs laser system using an S-1 photo multiplier surface; see Reference 5. Another laser that appears promising is the recently developed GaAs - GaP injection laser which radiates in the visible at 0.635 um and is capable of 25 watts peak output power at room temperature.

3.0 Acknowledgement

The author has benefited from having worked with M. Kolker and R. Wilmotte on the subject of the use of lasers for deep space communications.

4.0 References

### TABLE 1

**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, ( \lambda = 0.84 ) ( \mu )m</td>
<td>S-1 Photomultiplier</td>
<td>DDS 64, TRS 89</td>
</tr>
<tr>
<td>2</td>
<td>Semiconductor in visible, ( \lambda = 0.42 ) ( \mu )m (unavailable)</td>
<td>S-20 Photomultiplier</td>
<td>DDS 7.5, TRS 9.9</td>
</tr>
<tr>
<td>3</td>
<td>Argon II, ( \lambda = 0.48 ) ( \mu )m</td>
<td>S-20 Photomultiplier</td>
<td>DDS 208, TRS 274</td>
</tr>
<tr>
<td></td>
<td>( \text{N}_2 - \text{CO}_2 )</td>
<td>Ideal Detector* (unavailable)</td>
<td>DDS 111, TRS 134</td>
</tr>
<tr>
<td>5</td>
<td>Ho-doped YAG, ( \lambda = 2.3 ) ( \mu )m</td>
<td>Ideal Detector* (unavailable)</td>
<td>DDS 20, TRS 27</td>
</tr>
</tbody>
</table>

**Microwave:**

(a) 3 GHz S-band system: diameter = 2000 cm  
(b) 35 GHz Ka-Band system: diameter = 1000 cm

**NOTES:**

Distance = 180 million km  
Power input to transmitter = 30 watts  
Information rate = \( 10^7 \) 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, \( B_T = 10^8 \) Hz

*An ideal detector is assumed to be one that has no internal noise and which has sufficient gain so that the thermal noise at the detector output is negligible with respect to the shot and background noise.
1. $n_{LH} \text{ vs } x_b/2 \text{ for } x_{SN} = 10$
\[ D = \frac{B_T}{H_B} \]

\[ X_{SN} = 10 \]

2. \( n_{TR} \) vs. \( X_B/2 \) for \( X_{SN} = 10 \)
3. $n_{DD}$ vs $x_b$ for $x_{SN} = 10$
4. Relative Performance of TRS and LHS for $X_{SN} = 10$
5. Relative Performance of DDS and LHS for $X_{SN} = 10$
6. Relative Performance of TRS and LHS for $X_{SN} = 3$
7. Relative Performance of TRS and LHS for $X_{SN} = 50$
8. Receiver Collecting Aperture Loss, \( L \), versus \( x_b \) for DDS when \( x_{SN} = 10 \)
9. $L_K$ versus $X_b$ for DDS when $X_{SN} = 10$