# A Note on Deep Space Optical Communication Link Parameters

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*Communication link analysis at the optical frequencies differs significantly from that at microwave frequencies such as the traditional S- and X-bands used in deep space applications, due to the drastically different technology of transmitter, antenna, modulators, receivers, etc. In addition, the important role that quantum noise plays in limiting system performance is quite different than that of thermal noise. In this paper, optical communication is discussed in the context of a deep space communication link. The optical link design is put in a design control table format similar to a microwave telecom link design. Key considerations unique to the optical link are briefly discussed.*

## I. Introduction

We have made a preliminary attempt to present the parameters influencing the performance of a deep space optical communication system in the same "design control table" format as that used in the design of microwave systems. This form of presentation facilitates comparison between the two types of systems. However, the optical and microwave systems are not completely analogous, and thus the presentation must be issued with several caveats to prevent misunderstanding.

The free space optical link differs from familiar microwave links in that its performance is limited by intrinsic quantum mechanical measurement uncertainty (loosely termed "quantum noise") and, occasionally, by background light levels, rather than by receiver thermal noise. The quantum noise contributes generally non-Gaussian statistics, and consequently analyses of the optical and microwave links are quite different. Performance in the case of a Gaussian noise-limited microwave link is completely summarized by a signal-to-noise ratio $E_s/N_0$, where $E_s$ is the received signal energy per bit and $N_0$ is the (single-sided) noise spectral density level. Unfortunately, for a quantum noise-limited optical link, there is no comparably handy ratio that fully characterizes performance.

It is nonetheless convenient to go ahead and normalize the received optical energy relative to a reasonable measure of the quantum noise level. In the optical communications literature, it is standard to normalize optical signal energies to units of photons. This can be loosely interpreted as a signal-to-noise ratio, to the extent that the "amount" of quantum noise is roughly indicated by the energy $h\nu$ of a single photon ($h$ = Planck's constant, $\nu$ = optical frequency). It must be remembered, however, that this ratio is not sufficient by itself to specify performance, even when only quantum noise is present. Performance of the optical system depends in a complicated way on the number of detected signal photons and background photons, and also on the kinds of signal modulation, receiver structure, and information coding that are used.

## II. Sample Optical Design Control Table

A nominal design control table (DCT) for a sample deep space optical link is given in Table 1. The sample link consists of a free space downlink from the vicinity of Jupiter at 5 AU to an Earth-orbiting relay station. Parameter values appearing in the table are largely drawn from Refs. 1 and 2, which analyzed the optical deep space link in some detail.

A brief overview of the sample optical link DCT is helpful. The first seven entries calculate the detected power at the receiver due to the transmitted signal. The assumed values for transmitter power, antenna gains, and receiver losses correspond to similar assumptions in Refs. 1 and 2, and they represent current or foreseeable technological capabilities. Entries 8-10 in the table estimate the net detected power at the receiver due to typical sources of background light. In this example, the receiver's field of view is assumed to take in light from either a typical point source (weak star, magnitude +6) or a typical distributed source (Jupiter at opposition). Background sources as strong as these may or may not be present in an actual application; stronger sources (e.g., bright stars, sun, skylight for ground-based receivers) might also cause problems in certain configurations. Entries 11-13 normalize the signal and background power relative to the bit rate. Entries 14-16 further normalize these bit energies to units of photons. The last two entries calculate the link performance and margin for the assumed modulation, coding, and detection schemes.

A brief annotation of each of the individual entries in the sample DCT follows:

(1) The assumed transmitter power value of 1 watt refers to the total power broadcast from the transmitting antenna; i.e., it includes internal transmitter inefficiencies as well as losses in coupling the transmitter to the antenna.

(2) The transmitting antenna gain is computed as $4\pi A_t/\lambda^2$, where the transmitter wavelength $\lambda$ is taken as 1 micron and the effective transmitting area $A_t$ is taken as $1/4 \mathrm{m}^2$. This value of $A_t$ requires 56-cm-diameter optics if diffraction limited.

(3) The 2-dB pointing loss was computed for 1/2-$\mu$rad rms error from curves in Section 2.7 of Ref. 2. The 1/2-$\mu$rad rms error level corresponds to approximately 1/4 beam width. This level was chosen as a threshold beyond which performance degrades very rapidly, and as such it represents a stringent requirement on pointing accuracy.

(4) Space loss is determined from the formula $(4\pi R/\lambda)^2$, where the assumed range is $R = 5$ AU.

(5) The receiving antenna gain is computed as $4\pi A_r/\lambda^2$, where the receiving area $A_r$ is taken to be $10 \mathrm{m}^2$. This corresponds to 3.6-m-diameter receiving optics, not necessarily diffraction-limited.

(6) Total losses at the receiving end are listed as 8 dB. Three contributions to the figure are itemized separately. The atmospheric loss entry of 0 dB is included just to illustrate one of the advantages of a deep space relay link as compared to familiar direct links to Earth. The -1 dB receiver transmission loss and -7 dB detector quantum efficiency correspond to factors $\zeta_r = 0.8$ and $\eta_r = 0.2$ used in Refs. 1 and 2. The factor $\zeta_r$ accounts for receiving antenna losses, and the factor $\eta_r$ refers to the probability of detecting individual photons at the receiver.

(7) The net detected signal power entry is simply the sum (in dB) of entries 1 through 6.

(8) The background intensity of -97 dBm is taken from Fig. 1-4 and Eq. (1-4) of Ref. 2, assuming wavelength $\lambda = 1$ $\mu$m, optical predetection bandwidth $\Delta\lambda = 10$Å, and receiving area $A_r = 10 \mathrm{m}^2$, for either of two cases:

   (a) weak star, magnitude +6, or

   (b) Jupiter at opposition, as seen with receiver field of view $\theta_r = 2$ $\mu$rad.

   The assumed field of view (for the distributed source case) is taken to be the same as the transmitted beamwidth; it does not require diffraction limited receiving optics.

(9) The same losses at the receiving end apply to both signal and background power, and therefore entry 6 is repeated here.

(10) The net detected background power entry is the sum (in dB) of entries 8 and 9.

(11) The assumed bit rate of 1 Mbps is approximately 9 times the capability of the Voyager system from Jupiter.

(12) Detected signal energy per bit $E_s$ is obtained by dividing detected signal power by bit rate.

(13) Detected background energy per bit $E_b$ is obtained by dividing detected background power by bit rate.

(14) 'Quantum noise' energy is measured by $h\nu$, as discussed above.

(15) The "signal-to-quantum noise ratio" $E_s/h\nu$ is obtained from entries 12 and 14. In the optical literature it is conventional to use the photon information rate $\rho = (E_s/h\nu)^{-1}$ rather than $E_s/h\nu$.

(16) The "background-to-quantum noise ratio" $E_b/h\nu$ is obtained from entries 13 and 14.

(17) Required $E_s/h\nu$ represents the net effect of many different system parameters. The calculation here assumes uncoded 64-ary PPM modulation and a direct detection receiver. A value of required $E_s/h\nu$ = 1 (0 dB) to achieve a bit error rate of $5 \times 10^{-3}$ is listed in the table. Additional performance results are discussed in the next section.

(18) The nominal link margin of 3 dB is obtained from entries 15 and 17.

## III. Key Uncertainty Areas and Tradeoff Considerations

Table 1 demonstrates the potential feasibility of communicating over a 5-AU free space optical link at a rate of 1 Mbps, assuming the parameter values listed. We have attempted to choose values which are not overly optimistic or conservative for near-future optical systems. However, because of the relative immaturity of optical technology, these numbers are stated with much less certainty than the corresponding parameters in a microwave system.

There are several key areas of uncertainty concerning parameters which directly affect the amount of signal power obtained at the receiver:

(1) The assumed transmitted power of 1 watt is beyond current technological capabilities, and further development of efficient, high-power, narrow-beam optical sources is needed. Advances in optimizing the power efficiency of semiconductor injection lasers (Ref. 3) and in phase locking laser arrays to produce a strong coherent source (Ref. 4) are currently underway.

(2) The assumed optical antenna dimensions are modest compared to those of corresponding microwave antennas or of Earth-based telescopes, but the technology of low weight, spaceborne optical antennas is still in its infancy. Improvements are expected, with the experience gained from such projects as the Infrared Astronomy Satellite (IRAS) (Ref. 5).

(3) Very precise pointing and tracking systems need to be developed. To keep pointing loss reasonably low, pointing errors must be limited to submicroradian levels. The nominal 2-dB loss assumed in the table could be increased radically if this level of accuracy is not obtainable.

(4) Required $E_s/h\nu$ depends on many different system parameters, including the desired bit error rate, the amount of background noise, and the kinds of signal modulation, receiver structure, and information coding that are used. The 0-dB value assumed in the table corresponds to a photon information rate of 1 bit/photon. This value may be raised or lowered significantly if changes are made in the system parameters. For example, eliminating the assumed background noise entirely would reduce required $E_s/h\nu$ to -1 dB, whereas higher background levels might raise the required $E_s/h\nu$ intolerably. A tighter error tolerance would require higher $E_s/h\nu$, for instance, $E_s/h\nu$ = 4 dB for a bit error rate (BER) of $10^{-6}$ in the absence of background. The requirement at this BER could be drastically reduced via coding (e.g., to a required $E_s/h\nu$ = −3 dB with a (63, 32) Reed-Solomon code) or by using a larger number of PPM slots (e.g., required $E_s/h\nu$ = 1 dB for $M$ = 4096). Ultimate capacity of the quantum limited PPM/direct detection channel is unbounded, and thus in principle the required $E_s/h\nu$ may be made arbitrarily small at any BER, but practical limits on coding complexity and on laser peak power levels[1] generally restrict these gains to a few dB relative to Table 1. Presently, a laboratory effort (Ref. 6) is in progress to demonstrate the feasibility of communicating at 2.5 bits/photon with currently available devices. Heterodyne and homodyne receiver structures applied to the quantum limited channel have finite capacities of 1 nat/photon and 2 nats/photon, respectively (corresponding to finite lower bounds on $E_s/h\nu$ of -1.6 dB and -4.6 dB), but these structures may be preferable to direct detection in certain applications.

The following table illustrates some of the tradeoff issues involved in the determination of the required $E_s/h\nu$. For the purpose of this illustration, a direct detection receiver is used and background noise is assumed to be negligible. Required $E_s/h\nu$ is given as a function of the number of PPM slots ($M$) and the required BER for the two cases of uncoded transmission and rate 1/2 ($M$ - 1, M/2) Reed-Solomon coding. By way of comparison, the 2.5 bits/photon ($E_s/h\nu$ = -4 dB) laboratory demonstration (Ref. 6) uses $M$ = 256 and a rate 3/4 (255, 191) Reed-Solomon code.

[1] At a fixed average power level (e.g., 1 watt in Table 1), the peak power required of the transmitting laser increases directly with $M$, the number of PPM slots.

# References


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**Table 1. Jupiter to earth-orbiting relay optical link**

| | | | |
|---|---|---|---|
| 1. | Transmitted power (1 watt) | | 30 dBm |
| 2. | Transmitting antenna gain ($A_t$ = 1/4 $m^2$, $\lambda$ = 1 $\mu$m) | | 125 dB |
| 3. | Pointing loss (1/2 $\mu$rad rms error) | | −2 dB |
| 4. | Space loss (R = 5 AU, $\lambda$ = 1 $\mu$m) | | −380 dB |
| 5. | Receiving antenna gain ($A_r$ = 10 $m^2$, $\lambda$ = 1 $\mu$m) | | 141 dB |
| 6. | Losses at receiving end | | −8 dB |
| | Atmospheric loss | −0 dB | |
| | Receiver transmission loss | −1 dB | |
| | Detector efficiency | −7 dB | |
| 7. | Net detected signal power | | −94 dBm |
| 8. | Background intensity (Jupiter at opposition or weak star, 10A bandwidth, $A_r$ = 10 $m^2$, $\theta_r$ = 2 $\mu$rad) | | −97 dB |
| 9. | Losses at receiving end | | −8 dB |
| 10. | Net detected background power | | −105 dBm |
| 11. | Bit rate (1 Mbps) | | 60 dB Hz |
| 12. | Detected signal energy/bit ($E_s$) | | −154 dB mJ |
| 13. | Detected background energy/bit ($E_b$) | | −165 dB mJ |
| 14. | "Quantum noise" ($h\nu$) | | −157 dB mJ |
| 15. | $E_s/h\nu (=1/\rho)$ | | 3 dB |
| 16. | $E_b/h\nu$ | | −8 dB |
| 17. | Required $E_s/h\nu$ $(=1/\rho)$ | | 0 dB |
| 18. | Margin | | 3 dB |

**Table 2. Required $E_s/h\nu$ for quantum limited direct detection of PPM signals**

| Required $E_s/h\nu$ (in dB), No Coding | | | | | Required $E_s/h\nu$ (in dB), $(M-1, M/2)$ R-S coding | | | | |
|---|---|---|---|---|---|---|---|---|---|
| BER \ M | 16 | 32 | 64 | 256 | BER \ M | 16 | 32 | 64 | 256 |
| $10^{-7}$ | 5.9 | 4.9 | 4.1 | 2.8 | $10^{-7}$ | 1.3 | −1.1 | −3.0 | −5.8 |
| $10^{-6}$ | 5.2 | 4.2 | 3.4 | 2.1 | $10^{-6}$ | 0.9 | −1.4 | −3.3 | −6.0 |
| $10^{-5}$ | 4.3 | 3.4 | 2.6 | 1.3 | $10^{-5}$ | 0.3 | −1.9 | −3.6 | −6.1 |
| $10^{-4}$ | 3.3 | 2.3 | 1.5 | 0.3 | $10^{-4}$ | −0.4 | −2.4 | −4.0 | −6.4 |
| $10^{-3}$ | 1.9 | 0.9 | 0.2 | −1.1 | $10^{-3}$ | −1.2 | −3.0 | −4.5 | −6.6 |
| $10^{-2}$ | −0.1 | −1.1 | −1.9 | −3.1 | $10^{-2}$ | −2.3 | −3.9 | −5.1 | −7.0 |