Deep-Space Optical Communication Link Requirements

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Link Equation:

For a free-space optical link the signal count per bit period is given by[1,2]

$$
\begin{aligned}
&K_{bit} = \eta_{atmos}\eta_{trans}\eta_{rcvr}\eta_{\det}\frac{P_{trans}T_{bit}}{h\nu}\left(\frac{\pi d_{trans}}{\lambda}\right)^2\left(\frac{\pi d_{rcvr}}{\lambda}\right)^2\left(\frac{\lambda}{4\pi z}\right)^2 \\
&K_{bit} = signal\ \ photon\ \ count\ \ per\ \ bit \\
&\eta_{atmos} = 1-way\ \ atmospheric\ \ transmittance \\
&\eta_{trans} = efficiency\ \ of\ \ transmitter\ \ optics \\
&\eta_{rcvr} = efficiency\ \ of\ \ receiver\ \ optics \\
&\eta_{\det} = detector\ \ quantum\ \ efficiency \\
&d_{trans} = transmitting\ \ telescope\ \ diameter\ (m) \\
&d_{rcvr} = receiving\ \ telescope\ \ diameter\ (m) \\
&\nu = optical\ \ frequency\ (Hz) = c/\lambda \\
&\lambda = optical\ \ wavelength\ (m) \\
&c = 3x10^8\ m/s \\
&z = pathlength\ (m) \\
&P_{trans} = transmitter\ \ average\ \ power\ (W) \\
&h = Planck's\ \ constant = 6.626x10^{-34}\ J\bullet s
\end{aligned} \qquad . \qquad (1)
$$

Required Signal Count:

The required signal count per bit depends on the desired bit error rate (BER), level of the background count, modulation/detection format and coding strategy. A nominal value of 100 counts/bit should enable the system to achieve raw (uncoded) bit error rates between 10^{-6} and 10^{-9}, depending on the background noise level (4-ary PPM)[2]. This is a worst-case (large signal requirement) estimate derived by assuming a background level of about 5 counts/bit using an avalanche photodiode with an excess noise factor of 5. The best-case (low signal requirement) can be derived by assuming the receiver employs a perfect photon counting detector with no dark counts and no background noise. In this case the bit error rate (BER) is approximately equal to the probability of receiving zero counts within the time slot (binary PPM).

$$
\begin{aligned}
&BER \simeq \Pr ob(count = 0) = \exp(-K_{bit}) \\
&K_{bit} \simeq -\ln(BER)
\end{aligned} \qquad (2)
$$

Depending on the efficiency of the error correcting codes, the raw BER should be no larger than about 10^{-5}-10^{-6}, which implies that the minimum value of K_{bit} is approximately 10-15. Since it will not be possible to eliminate the background noise entirely, we assume a best-case value of 25.

Assumption: $$25 \le K_{bit} \le 100 \tag{3}$$

Transmitting Optics:

The diameter of the transmitting telescopes for both the spacecraft and ground station are limited by pointing accuracy. To ensure reliable communications, the transmitting beam width (λ / d_{trans}) should be no smaller than 10 times the uncorrected pointing jitter[2] ($\Delta\phi_{trans}$).

$$\begin{aligned} 10\Delta\phi_{trans} &\le \lambda / d_{trans} \\ d_{trans} &\le \lambda / (10\Delta\phi_{trans}) \end{aligned} \tag{4}$$

We assume a pointing jitter of 0.1 μrad. As a point of reference, the Earth's diameter is approximately 8,000 miles and its farthest distance from Mars is 250 million miles. From Mars, the Earth's disk subtends a planar angle of 32 μrad. Pointing to 0.1 μrad accuracy from Mars is equivalent to hitting a spot 25 miles in diameter on the Earth! I don't think we are likely to do much better than this value. In fact to achieve this accuracy we need to employ a beacon laser at the ground station and implement the spatial tracking at a shorter wavelength to take advantage of the enhanced telescope resolution ($\lambda_{beacon} / d_{rcvr}$) at shorter wavelengths. The ground station transmitter would also require adaptive optics with a spacecraft beacon (see below) to point to the required 0.1 μrad in the presence of atmospheric turbulence.

Assumptions (for both spacecraft and ground station):

$$\begin{aligned} \lambda &\simeq 1\mu m \\ \Delta\phi_{trans} &= 0.1\mu rad \\ d_{trans} &= 1m \end{aligned} \tag{5}$$

Receiving Optics:

The diameter of the receiving optics on the spacecraft is limited by mass and size. Given that the surface curvature must be held to optical tolerances, 1-2 meter would appear to be a practical limit. On the spacecraft, the transmitting and receiving optics are shared so we assume $d_{rcvr}\big|_{spacecraft} = 1m$. The effective diameter of the receiving optics for the ground station, which must include adaptive optics to mitigate the effects of atmospheric turbulence (see below), is limited only by cost.

Assumptions:

$$\begin{aligned} d_{rcvr}\big|_{spacecraft} &= 1m \\ d_{rcvr}\big|_{ground\ \ station} &\gg 1m \end{aligned} \tag{6}$$

Background Noise:

The background noise level is a strong function of wavelength. The dominant sources of background noise for both the uplink and downlink are solar scattering in the Earth's atmosphere and airglow emissions from the Earth's upper atmosphere. The laser wavelength can be chosen to minimize the effects of both noise sources by avoiding strong airglow lines and if possible choosing a wavelength corresponding to one of the deep solar Fraunhofer lines. Furthermore, the ground station telescope must employ adaptive optics to achieve a near diffraction limited field-of-view, which would minimize background noise. In this analysis we assume the desired error rate can be achieved in the presence of background noise when $K_{bit} = 100$. In the absence of background noise, $K_{bit} = 25$.

Optical Telescope and Detector Efficiencies and Site Requirements:

We assume that the transmitting and receiving optics and the detector all have efficiencies of about 85% while the 1-way atmospheric transmittance is 70%. This latter assumption means the ground station must be located where the air is clear most of the time. Because the telescope would also be equipped with adaptive optics so that very narrow fields-of-view and precise uplink pointing could be employed, the site should also have good seeing (large r_0).

Assumptions:

$$\begin{aligned} &\eta_{trans} \simeq \eta_{rcvr} \simeq \eta_{\det} \simeq 0.85 \\ &\eta_{atmos} \simeq 0.70 \\ &\eta_{atmos}\eta_{trans}\eta_{rcvr}\eta_{\det} \simeq 0.43 \\ &r_0 = 10cm @ \lambda = 1\mu m \end{aligned} \tag{7}$$

Temporal Tracking:

Phase-locked-loops (PLL) provide an easily implemented method for recovering the transmitter timing in both RF and optical communication systems[3,4]. The RMS timing error for a binary optical PPM system employing PLL synchronization is given by[4]

$$\frac{\Delta T_{bit}}{T_{bit}} \simeq \frac{1}{2\pi}\sqrt{\frac{T_{bit}B_{PLL}}{K_{bit}}} \quad , \tag{8}$$

where B_{PLL}(Hz) is the closed-loop bandwidth of the PLL. The loop bandwidth must be large enough to track the high frequency fluctuations in detected signal phase induced by atmospheric turbulence, which can be substantial[5]. The characteristic bandwidth of atmospheric turbulence is about 1 kHz. We assume B_{PLL}=10 kHz so that the loop can follow the high frequency phase fluctuations. For this case, even for a relatively low data rate of 10 Mbs and low signal level (K_{bit} = 25), the timing error would be only about 0.1% of the bit period. In fact the loss factor associated with temporal tracking errors will be negligible whenever the loop bandwidth is less than about 0.1% of the bit frequency[4].

Spatial Tracking and Beacon Requirements:

In addition to introducing random phase fluctuations into the detected bit stream, atmospheric turbulence also limits the resolution (and field-of-view) of the ground-based receiving telescope and the pointing accuracy of the uplink transmitting telescope. Adaptive imaging technologies, similar to those developed for ground-based astronomical telescopes, can be employed to mitigate the effects of turbulence. The performance of adaptive optics systems depends on the seeing conditions at the site and the brightness of the guide star, which in some cases is created in the mesospheric Na layer with lasers. Na laser guide stars would not be required for optical communication links because the communication laser signal or a laser beacon signal can be used to drive the adaptive optics system. To reduce the RMS wavefront error of the adaptively corrected telescope to $\lambda / 17.5$ would require a sub-aperture size and beacon photon flux density of[6]

$$\begin{aligned} &Optimum\ \ subaperture\ \ diameter = 0.69 r_0 \\ &Beacon\ \ photon\ \ flux\ \ density / sample\ \ period = 76.3 / r_0^2\ / T_{scnt} \end{aligned} \tag{9}$$

where r_0 is the seeing cell diameter and T_{scnt} is the scintillation time of the atmosphere. The ground stations should be located at sites with good seeing (large r_0) and an abundance of clear weather. We assume a nominal value of r_0=10 cm and T_{scnt}=1 ms, which is affected by the wind speed. In this case the required beacon flux density is 7.63 x 10^6 photons/m^2/s. The required flux density (photons/m^2/s) for the downlink to drive the adaptive optics system can be derived from (1) in terms of the required K_{bit}.

$$\begin{aligned} &\frac{76.3}{r_0^2 T_{scnt}} \le \frac{4K_{bit}}{\pi d_{rcvr}^2 T_{bit}} = \frac{\eta_{atmos}\eta_{trans}\eta_{rcvr}\eta_{\det} \frac{P_{trans}}{h\nu}\left(\frac{\pi d_{trans}}{\lambda}\right)^2}{4\pi z^2} \\ &\frac{959 h\nu z^2}{\eta_{atmos}\eta_{trans}\eta_{rcvr}\eta_{\det}\left(\pi d_{trans} / \lambda\right)^2 r_0^2 T_{scnt}} = (2.12x10^{-12} z)^2 \le P_{trans} \end{aligned} \tag{10}$$

As we will see later, this criterion is easy to satisfy for both the mid- and far-term data rate requirements at 1 AU and for the Mars-Earth link with laser powers of about 1 W. The spacecraft communication laser can easily serve as the beacon for spatial tracking.

Transmitter Power and Data Rate:

For a given error rate, the required transmitting laser power is proportional to the data rate. That is doubling the desired data rate would require the laser power to double, assuming all other system parameters remained the same. We assume the downlink data rate is considerably higher than the uplink rate because uplink command and control is less data intensive than instrument data acquisition. Furthermore, we assume that power limitations on the spacecraft would limit the transmitter power to about 10 W while the uplink power would only be limited by laser technology.

Assumptions (Mid-Term 2017-2022):

$$\begin{aligned} T_{bit}\big|_{downlink} &= 5x10^{-9}\,s\ (200Mbs) \\ P_{trans}\big|_{downlink} &= 10W \\ T_{bit}\big|_{uplink} &= 5x10^{-8}\,s\ (20Mbs) \\ P_{trans}\big|_{uplink} &= 100W \\ z_{AU} &= 1\ AU = 1.5x10^{11}\,m \\ z_{ME} &= Mars - Earth = 4x10^{11}\,m \end{aligned} \qquad (11)$$

Assumptions (Far-Term 2023-2028):

$$\begin{aligned} T_{bit}\big|_{downlink} &= 5x10^{-11}\,s\ (20Gbs) \\ P_{trans}\big|_{downlink} &= 100W \\ T_{bit}\big|_{uplink} &= 5x10^{-9}\,s\ (200Mbs) \\ P_{trans}\big|_{uplink} &= 1000W \\ z_{AU} &= 1\ AU = 1.5x10^{11}\,m \\ z_{ME} &= Mars - Earth = 4x10^{11}\,m \end{aligned} \qquad (12)$$

Downlink Requirements (Mid-Term):

In the following calculations we assume that the spacecraft parameters are fixed and we compute the required ground station telescope diameter and laser power required to achieve the downlink and uplink data rates. After substituting the assumed values (best-case) for the system parameters into (1) and solving for the diameter of the receiving telescope at the ground station, we obtain.

$$d_{rcvr} = \frac{4\lambda z}{\pi d_{trans}} \sqrt{\frac{K_{bit} hc / \lambda}{\eta_{atmos}\eta_{trans}\eta_{rcvr}\eta_{\det} P_{trans} T_{bit}}} = 1.94x10^{-11} z \qquad (13)$$

For a 1 AU link where z = 1.5 x 10^{11} m, $d_{rcvr}\big|_{ground\ \ station} = 2.9m$. For a Mars-Earth link where the maximum z = 250 million miles = 4x10^{11}m, $d_{rcvr}\big|_{ground\ \ station} = 7.8m$. These requirements seem readily achievable with current technology. The most challenging requirement is the laser power. If we reduce the spacecraft laser power to 1 W from 10 W, then the required telescope diameter for the ground station increases by a factor of 3.16 to 9.16 m and 24.5 m, respectively for the 1 AU and Mars-Earth links.

Uplink Requirements (Mid-Term):

For the uplink we assume that the beam width and hence the effective transmitting aperture diameter is limited by the pointing jitter to 1 m, the same as the spacecraft transmitting aperture (i.e. $\Delta\phi_{trans} = 0.1\mu rad$). After substituting the assumed values (best-case) for the system parameters into (1) and solving for the laser transmitter power at the ground station we obtain.

$$P_{trans} = \frac{K_{bit} hc / \lambda}{\eta_{atmos}\eta_{trans}\eta_{rcvr}\eta_{\det}T_{bit}} \left(\frac{4\lambda z}{\pi d_{rcvr} d_{trans}} \right)^2 = (1.94x10^{-11} z)^2 \quad (14)$$

For a 1 AU link where z = 1.5 x 10^{11} m, $P_{trans}\big|_{uplink} = 8.5W$. For a Mars-Earth link where the maximum z = 250 million miles = 4x10^{11}m, $P_{trans}\big|_{uplink} = 60W$. These requirements seem readily achievable with current technology. Note, if we require the same data rate on the uplink as the downlink, then the uplink laser power levels must be increased by a factor of 10.

Downlink Requirements (Far-Term):

After substituting the assumed values (best-case) for the system parameters into (1) and solving for the diameter of the receiving telescope at the ground station we obtain.

$$d_{rcvr} = \frac{4\lambda z}{\pi d_{trans}} \sqrt{\frac{K_{bit} hc / \lambda}{\eta_{atmos}\eta_{trans}\eta_{rcvr}\eta_{\det}P_{trans}T_{bit}}} = 6.12x10^{-11} z \quad (15)$$

For a 1 AU link where z = 1.5 x 10^{11} m, $d_{rcvr}\big|_{ground\ station} = 9.2m$. For a Mars-Earth link where the maximum z = 250 million miles = 4x10^{11}m, $d_{rcvr}\big|_{ground\ station} = 24.5m$. These requirements seem achievable with current technology but in the Mars-Earth case would require a receiving telescope array and would be expensive. The most challenging requirement is the laser power. If we reduce the spacecraft laser power to 10 W from 100 W, then the required telescope diameter for the ground station increases by a factor of 3.16 to 29 m and 77 m, respectively for the 1 AU and Mars-Earth links.

Uplink Requirements (Far-Term):

For the uplink we assume that the beam width and hence the effective transmitting aperture diameter is limited by the pointing jitter to 1 m (i.e. $\Delta\phi_{trans} = 0.1\mu rad$). After substituting the assumed values (best-case) for the system parameters into (1) and solving for the laser transmitter power at the ground station we obtain.

$$P_{trans} = \frac{K_{bit} hc / \lambda}{\eta_{atmos}\eta_{trans}\eta_{rcvr}\eta_{\det}T_{bit}} \left(\frac{4\lambda z}{\pi d_{rcvr} d_{trans}} \right)^2 = (6.12x10^{-11} z)^2 \quad (16)$$

For a 1 AU link where z = 1.5 x 10^{11} m, $P_{trans}\big|_{uplink} = 84W$. For a Mars-Earth link where the maximum z = 250 million miles = 4x10^{11}m, $P_{trans}\big|_{uplink} = 600W$. These requirements seem achievable with reasonable advances in current technology. Note, if we require the same data rate on the uplink as the downlink, then the uplink laser power levels must both be increased by a factor of 10.

References

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