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A study of a ground-to-satellite optical communication link with multiple uplink laser beams

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1. Introduction

Optical communication links between the ground and satellite optical systems are adversely affected by the scintillation due to the turbulent atmosphere,[1] and a possible method to compensate atmospheric turbulence-induced scintillation is to use an adaptive optics system. Such a system, however, is not easily applied to a link between the ground and a low-earth-orbit (LEO) satellite. We therefore use a multibeam laser transmission system for the uplink,[2,3] and the optical link budget for the multibeam system is considered in this paper. The multibeam gain is estimated from the probability density function (PDF) of the multiple optical beams, and the aperture averaging effect is taken into account for the downlink path. The safety for human eyes is also taken into account by using the maximum permissible exposure (MPE).

2. Fade statistics for multiple beams

Atmospheric turbulence can cause an optical signal to fade to below the threshold signal level. The PDF of the optical signal becomes the lognormal distribution in the region of weak fluctuations, and the fade statistics for a single Gaussian beam was given by Ref. 4. The PDF of the optical signal with multiple beams changes from a lognormal to a Gaussian according to the central limit theorem when a larger number of beams are used. The effect of the multiple beams is to reduce the variance of the fluctuating optical signal and to improve the threshold signal level at a desired fade probability from the mean value. We define the multibeam gain as the degree of this improvement. That is, the fade level for the multiple beams is given by adding the fade level for a single beam and the multibeam gain. The multibeam gain is also used for the improvement in the surge level of the optical signal, which is the useful notation on the link design for a multibeam laser transmission system.

3. Definition of multibeam gain

Let us consider N parallel beams each of which is separated by a distance larger than atmospheric coherence length r_0. The fluctuations of the beams are statistically independent of each other. The multibeam PDF $p_{\mathrm{multi}}(I)$ is given by the N-fold convolution of each of the individual lognormal PDFs. Because there are no analytic expressions for the N-fold convolution of lognormal distributions,[5] we use the characteristic functions Φ_n of the PDF $p_n(\ )$ and the fast Fourier transforms (FFTs) for the numerical estimation:

$$p_{multi}(I) = \Im^{-1}\left[\Phi_1 \cdot \Phi_2 \cdots \Phi_N\right],$$

$$\Phi_n(a) = \int_{-\infty}^{\infty} p_n(x)\exp(iax)dx,$$

where $\Im^{-1}[\ ]$ is the inverse Fourier transform, n is the order of the beam, and each beam has one Nth of the total power. The multibeam gain G_{multi} is defined by

$$G_{multi} = 10\log(I_{multi} / I_T),$$

$$P_1(I \le I_T) = P_E \text{ and } P_{multi}(I \le I_{multi}) = P_E \text{ for fade,}$$

$$P_1(I \ge I_T) = P_E \text{ and } P_{multi}(I \ge I_{multi}) = P_E \text{ for surge,}$$

where P_1 and P_{multi} are respectively the cumulative probabilities below/above the threshold levels I_T (single beam) and I_{multi} (multibeam). P_E is the desired fade/surge probability of the optical link.

4. Link budget design for multiple beams

When a Gaussian beam with the $1/e^2$ beam waist ω is transmitted to a satellite at a distance L, the link equation is

$$P_R = P_T \cdot \tau_T \cdot G_T \cdot L_R \cdot G_R \cdot \tau_R \cdot \exp\left[-2\left(\frac{\Delta\theta}{\theta_0}\right)^2\right],$$

where

$$L_R = \left(\frac{\lambda}{4\pi L}\right)^2 \text{ and } \theta_0 = \frac{\lambda}{\pi\omega},$$

P_R is the average optical power received, P_T is the transmitting laser power, τ_T is the transmission loss, τ_R is the receiving loss, L_R is the free-space loss, θ_0 is the divergence of the Gaussian beam, and $\Delta\theta$ is the pointing loss. The transmitting antenna gain G_T and the receiving antenna gain G_R respectively are given by the equations in Refs. 6 and 7. The aperture averaging factor is calculated according to Ref. 8. Table 1 shows an example of the link budget design for eight laser beams when the Optical Inter-orbit Communications Engineering Test Satellite (OICETS) is used.[9] The fade probability at 10^{-6} is assumed in this case and the 30-degree elevation angle is considered as the worst case. The multibeam gains for fade and surge are estimated to be 9.7 dB and -6.2 dB. The mean receiving optical powers can be positive margins, however, the fade and surge levels as the fluctuation level should be within the dynamic range, 10 dB for the OICETS, of the optical receiver. For the downlink path the fade level will be improved by 10.1 dB by the aperture averaging.

Table 1. Link budget for an eight laser beams transmission system between the ground and the OICETS satellite.

Items	Uplink	Downlink
Wavelength	0.819 μm	0.847 μm
Data rate	2.048 Mbps	49.3724 Mbps
Laser power	10.9 dBm	20.0 dBm
Transmitting antenna diameter	1.0 cm	26.0 cm
Transmitter optics loss	-3.0 dB	-3.7 dB
Pointing loss	-3.0 dB	-3.0 dB
Beam divergence ($2\theta_0$)	156.0 μrad	8.8 μrad
Antenna gain	90.8 dB	113.4 dB
Free-space loss (L =1,000 km)	-263.7 dB	-263.4 dB
Atmospheric loss	-7.8 dB	-7.0 dB
Receiving antenna diameter	26.0 cm	10.0 cm
Antenna gain	119.6 dB	110.9 dB
Receiver optics loss	-4.1 dB	-3.0 dB
Receiving optical power (mean)	-60.3 dBm	-35.8 dBm
Required optical power	-69.5 dBm	-55.8 dBm
Margin (mean)	9.2 dB	20.0 dB
Fade level (single beam)	-15.2 dB	-16.7 dB
Multibeam gain	9.7 dB	—
Aperture averaging	—	10.1 dB
Fade level (multibeam)	-5.5 dB	-6.6 dB
Surge level (single beam)	13.2 dB	14.3 dB
Multibeam gain	-6.2 dB	—
Aperture averaging	—	-8.1 dB
Surge level (multibeam)	7.0 dB	6.2 dB

5. Safety of the laser beams

The MPE is an index of laser-radiation-level safety with regard to human eyes and bodies.[10,11] The MPE should be taken into account when building the laser transmitting system at the ground station. For the uplink path to the OICETS, the MPE is 1.94 mW/cm^2 when the wavelength is 0.819 μm and the bit rate is 2 Mbps. The permissible laser transmitting power at the optical antenna aperture is shown in Fig. 1 as a function of the antenna diameter. It is clear that multibeam transmission is with regard to meeting the MPE requirements: The transmitting power 12.2 mW reaches the MPE when eight beams 1.0 cm in diameter are used. Figure 2 shows, for various beam radii, the scintillation index as a function of uplink beam divergence. Decrease of the beam radius decreases the scintillation index with the beam divergence 156 μrad. The satellite tracking error should be taken into account when the beam divergence becomes narrow. The tradeoffs among the scintillation index, the satellite tracking error and the MPE need to be considered in the system design.

6. Conclusion

An optical link budget for multiple uplink beams was estimated. The multibeam gain derived from the PDF of the optical signal was introduced to describe the optical link budget. The optical link analysis for a multibeam laser transmission system will be handled easily by using the multibeam gain.

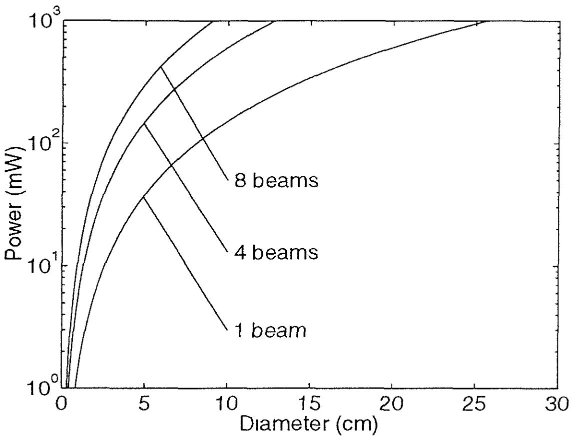

Fig. 1. Maximum permissible transmitting power at the telescope aperture versus antenna diameter. The MPE was taken into account in calculating these curves.

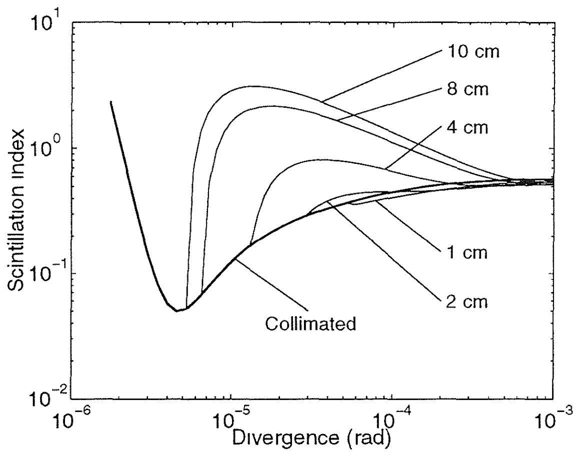

Fig. 2. Scintillation index as a function of uplink beam divergence ($2\theta_0$) for various beam radii. The refractive-index-structure parameter is H-V model: r_0=5.4 cm@λ=0.819 μm.

7. References

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