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Effects of Adaptive Optics on Performance of Laser Satellite Communications

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Abstract: We investigate Gaussian beam propagation from the ground to a LEO satellite, analyzing beam footprint, Strehl ratio, scintillation index, and bit-error rate under atmospheric turbulence with adaptive optics (AO) applied at the transmitter.

1. Introduction

In laser satellite communication systems, adaptive optics (AO) are employed at the ground-based transmitter to mitigate the effects of atmospheric turbulence on laser beam propagation and to reduce the bit error rate of the communication system [1–3]. The practical application of adaptive optics in vertical feeder links is discussed in detail in [4]. In addition to vertical links, adaptive optics are applicable to horizontal atmospheric paths [5], underwater optical links [6], and tissue imaging environments [7]. In this study, we analytically evaluate the performance of a laser satellite communication system under atmospheric turbulence in a vertical oblique path.

2. Formulation

The optical intensity of a Gaussian beam at the satellite altitude is derived using the extended Huygens-Fresnel principle as [8]

$$\begin{aligned} \langle I(\mathbf{p}, z = L) \rangle &= \frac{1}{(\lambda L)^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} u(\mathbf{s}_1) u^*(\mathbf{s}_2) \exp \left[\frac{jk}{2L} (|\mathbf{s}_1 - \mathbf{p}|^2 - |\mathbf{s}_2 - \mathbf{p}|^2) \right] \exp \left[-\frac{1}{2} D(\mathbf{s}_1, \mathbf{s}_2) \right] d^2\mathbf{s}_1 d^2\mathbf{s}_2 \\ &= A_s^2 \frac{\left(\frac{k\alpha_s}{2L} \right)^2}{\left(\frac{1}{4\alpha_s^2} + \frac{1}{\rho_0^2} + \frac{k^2\alpha_s^2}{4L^2} \right)} \exp \left[-\frac{\left(\frac{k\alpha_s}{L} \right)^2 (p_x^2 + p_y^2)}{\left(1 + \left(\frac{2\alpha_s}{\rho_0} \right)^2 + \left(\frac{k\alpha_s^2}{L} \right)^2 \right)} \right] \end{aligned} \quad (1)$$

where λ is the wavelength, L is the propagation distance, and $u(\mathbf{s})$ denotes the optical field at the source plane. In this study, we assume a collimated Gaussian beam given by $u(\mathbf{s}) = A_s \exp\left(-\frac{\mathbf{s}^2}{2\alpha_s^2}\right)$, where α_s represents the beam waist (source size), A_s is the amplitude of the source field. The vector $\mathbf{s} = (s_x, s_y)$ denotes the transverse coordinates in the transmitter plane, while \mathbf{s}_1 and \mathbf{s}_2 refer to two arbitrary points on that plane. $j = \sqrt{-1}$, and the wave number is $k = \frac{2\pi}{\lambda}$. The vector $\mathbf{p} = (p_x, p_y)$ represents the spatial coordinates in the receiver plane. The wave structure function is approximated as $D(\mathbf{s}_1, \mathbf{s}_2) \cong 2\rho_0^{-2} (\mathbf{s}_1 - \mathbf{s}_2)^2$, where ρ_0 is the coherence length for a spherical wave propagating through a vertical atmospheric path. We formulate the coherence length based on the power spectrum to facilitate the application of adaptive optics corrections

$$\rho_0 = \left\{ \frac{\pi}{6} k^2 \int_0^\infty \int_0^{2\pi} \int_0^L \kappa^3 \Phi(\kappa, C_n^2(h)) \left[1 - \sum_{\ell=1}^N F_\ell(\kappa, D, \theta) \right] d\kappa d\theta dh \right\}^{-3/5}, \quad (2)$$

where κ is the spatial frequency, $\Phi(\cdot)$ is the von Kármán power spectrum with $l_0 = 1\text{mm}$ and $L_0 = 50\text{m}$, $C_n^2(h)$ is the slant path profile of the structure constant as a function of altitude h and zenith angle ζ (i.e., Hufnagel-Valley), D is the aperture diameter of the adaptive optics system, the square bracket term represents the adaptive optics correction, $F_\ell(\kappa, D, \theta)$ is the filter function i.e. the Fourier transform of the Zernike polynomials [9].

The effective beam spot radius along the x-axis is found to be [7]

$$\sigma_x = \sqrt{\frac{2 \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} p_x^2 \langle I(\mathbf{p}, z=L) \rangle dp_x dp_y}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \langle I(\mathbf{p}, z=L) \rangle dp_x dp_y}} = \frac{L}{k} \sqrt{\frac{1}{\alpha_s^2} + \frac{4}{\rho_0^2} + \frac{k^2 \alpha_s^2}{L^2}}. \quad (3)$$

In Fig. 1 (a) and (b), the beam spot radius along the x-axis and the Strehl ratio are plotted versus the number of Zernike modes removed. In Fig. 1 (c), the cross-section of the beam intensity before and after removal of $N = 35$ Zernike modes is illustrated. The Strehl ratio is calculated as the ratio of the on-axis intensity with adaptive optics correction under turbulence to the on-axis intensity in a turbulence-free environment. The results indicate that adaptive optics corrections lead to a smaller beam spot radius, higher Strehl ratio, and greater intensity.

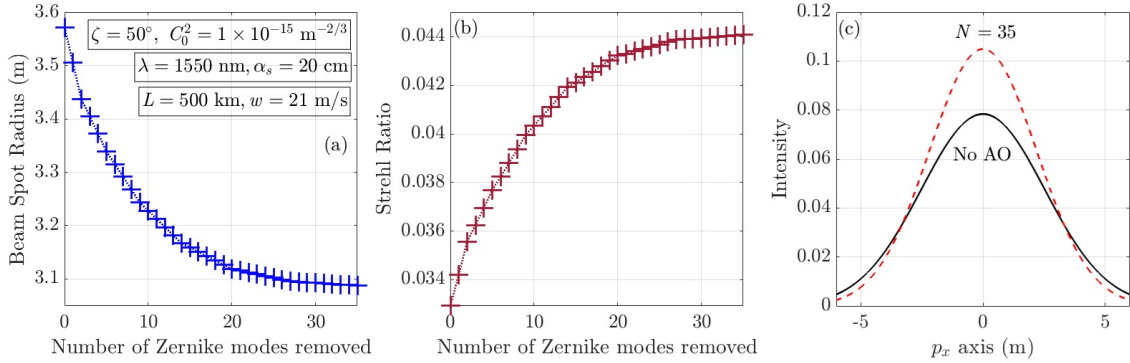


Fig. 1. (a) Beam spot radius along the x-axis, (b) Strehl ratio, versus the number of Zernike modes removed. (c) Cross-section of the beam intensity before adaptive optics (AO) and after removal of $N = 35$ Zernike modes.

When adaptive optics are applied, the scintillation index is given by [10, 11]

$$\sigma_B^2 = 4\pi k^2 \sec(\zeta) \int_0^\infty \int_0^{2\pi} \int_0^L \kappa \Phi_n(\kappa, C_n^2(h)) \left[1 - \sum_{\ell=1}^N F_\ell(\kappa, \gamma D, \theta) \right] \times \exp\left(-\frac{\Lambda L \kappa^2 \xi^2}{k}\right) \left\{ 1 - \cos\left[\frac{L \kappa^2}{k} \xi (1 - \bar{\Theta} \xi)\right] \right\} d\kappa d\theta dh, \quad (4)$$

where γ is the propagation parameter [11], $\Lambda = \Lambda_0 / (\Theta_0^2 + \Lambda_0^2)$, $\Lambda_0 = L / (k \alpha_s^2)$, $\Theta_0 = 1$, $\bar{\Theta} = 1 - \Theta$, $\Theta = \Theta_0 / (\Theta_0^2 + \Lambda_0^2)$, and $\xi = 1 - h/L$ is the normalized distance parameter. In Fig. 2, the scintillation index at the satellite level with adaptive optics correction and corresponding bit-error-rate are presented versus the number of Zernike modes removed.

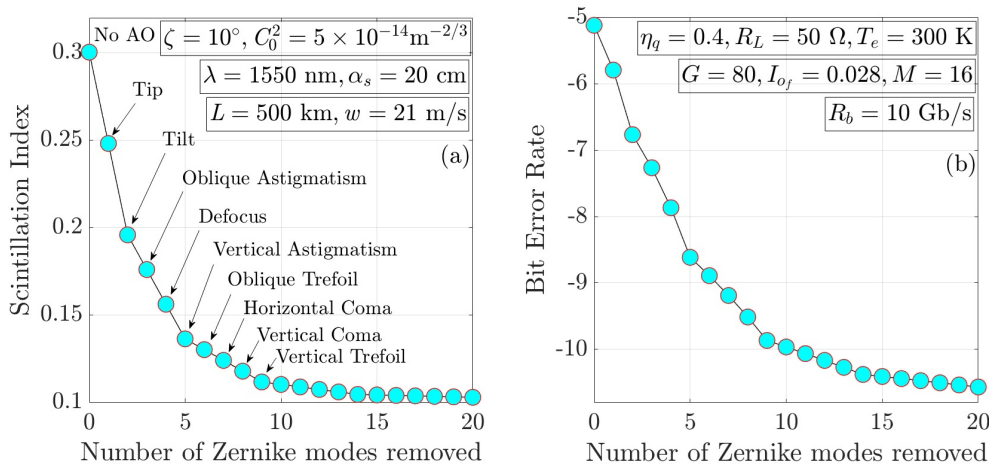


Fig. 2. (a) Adaptive optics corrected scintillation index, (b) logarithmic bit-error-rate (pulse-position modulated laser beam), versus the number of Zernike modes removed.

3. Results and Discussion

Implementing adaptive optics at the ground-based transmitter significantly enhances the performance of laser satellite communication systems. In future work, we will analyze how various system parameters influence the performance of a low-Earth orbit laser communication link utilizing adaptive optics at the transmitter. The isoplanatic angle will be incorporated into our work.

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