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Evaluation of the impact of atmospheric refraction on the bit error rate in the space-Earth optical communication channel

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Abstract. Classical optical communication allows the design of a high-speed data transmission channel between the spacecraft and the ground station. Its advantages are high interference resistance, high energy efficiency, low detectability, and significant potential for speed enhancement compared to radio communication. However, optical communication has a few technological limitations. This study investigates the contribution of atmospheric refraction to the value of bit error rate (BER). Preliminary results show a decrease in the signal-to-noise ratio as a function of the spacecraft's elevation angle, resulting in increased bit errors in data communication.

Keywords: free-space optical communication, space-Earth communication, atmospheric refraction, laser physics

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Оценка влияния атмосферной рефракции на величину битовой ошибки в оптическом канале связи космос-Земля

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Аннотация. Классическая оптическая связь позволяет организовать канал по высокоскоростной передачи данных с космических аппаратов на Землю. Среди ее преимуществ высокая помехозащищенность, высокая энергоэффективность, малозаметность и высокий потенциал увеличения скорости, в сравнении с радиосвязью. В этом исследовании изучается вклад явления астрономической рефракции в потенциальное значение величины битовой ошибки. Предварительные результаты

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показывают уменьшение соотношения сигнала к шуму в линиях связи между спутником и наземным приемником в зависимости от угла возвышения космического аппарата, что в свою очередь приводит к увеличению битовой ошибки при передаче данных.

Ключевые слова: оптическая связь в свободном пространстве, связь космос-Земля, атмосферная рефракция, лазерная физика

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Introduction

Space-ground optical communication requires an acquisition, pointing, and tracking system on both sides with a closed feedback loop consisting of a fast-steering mirror and a camera [1, 2]. However, during the operation of the guidance and stabilization system, the beacon laser signal transmitted from the Earth [3] and the telecommunication signal sent from the spacecraft experience different optical paths as they traverse the atmospheric layers. This results in an increased guidance error, which reduces the signal-to-noise ratio and leads to an increase in BER due to the Gaussian distribution of the beam intensity. In 2023, the Vector [4] payload was developed and successfully launched into orbit to demonstrate classical laser communication between satellite and ground station, and also to test some technical solutions and service systems.

Methods and results

From a structural perspective, the Earth's atmosphere can be represented as layers of a specified height, each possessing its own average temperature and pressure values. The refractive index of air can be calculated as [5]:

$$n = N \cdot 10^{-6} + 1, \tag{1}$$

where N is the reduced refractive index.

The reduced refractive index can be calculated as follows:

$$N = N_0 \cdot \frac{P \cdot T_0}{T \cdot P_0}, \tag{2}$$

where N_0 is an initial reduced refractive index, T_0 and P_0 represent the initial temperature and pressure in the layer with the refractive index N_0, respectively, T and P are the temperature and pressure in the layer with the refractive index N. For dry air, at a temperature of 273.15 K and a pressure of 760 mm Hg, the refractive index can be calculated as [6]:

$$N_0 = \left(103.38 + \frac{0.5854}{\lambda^4}\right)\frac{P}{T}, \tag{3}$$

where λ is the wavelength of radiation.

To estimate the divergence of the optical beam arriving on Earth from the spacecraft, the length must be determined while taking air refraction and the observation location into account. This quantity can be calculated based on the laws of geometric optics (see Fig. 1).

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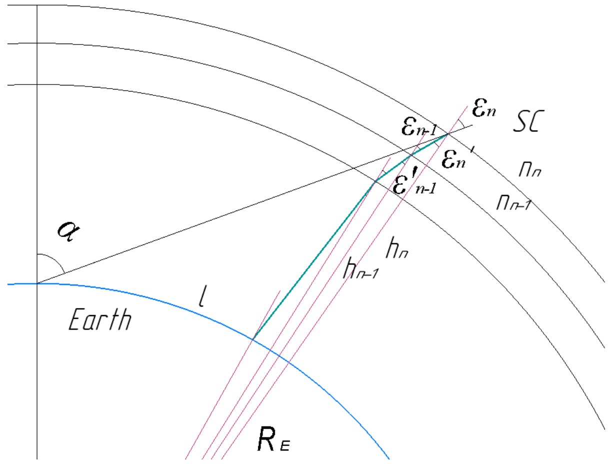

Fig. 1. Methodology for calculating atmospheric refraction: ε_n, ε'_n, ε_{n-1}, ε'_{n-1}, are the angles of incidence and refraction, h_n, h_{n-1} are the heights from the Earth to layers with refractive indices n_n, n_{n-1}, R_E is the radius of the Earth, α is the elevation angle of spacecraft, l is the length between the observation point and the deflected ray on the surface of the Earth

The signal-to-noise ratio (SNR) influences the BER, which is also impacted by the type of signal modulation used. The satellite Vector employs pulse position modulation (PPM), and the function of the BER is defined as [7]:

$$\mathrm{SNR}_2 = \mathrm{SNR}_1 \cdot e^{\left(-\frac{l^2}{2\cdot\sigma^2}\right)}, \tag{4}$$

where L is the number of time intervals (with $L = 4$ for PPM-4 encoding). Since the spot formed on Earth by the spacecraft exhibits a Gaussian distribution of energy E, the SNR at the center of this spot is expressed as:

$$\mathrm{SNR}_1 = E \cdot \frac{\frac{1}{\sigma\sqrt{2\pi}}}{\mathrm{Noise}}, \tag{5}$$

where σ is the standard deviation of the Gaussian distribution.

At a point offset by l from the center of the spot due to atmospheric refraction, the SNR can be expressed as:

$$\mathrm{SNR}_1 = \mathrm{SNR}_2 \cdot e^{\left(-\frac{l^2}{2\cdot\sigma^2}\right)}. \tag{6}$$

By assigning values to the channel parameters, one can obtain the BER for two different values of SNR (BER_2 / BER_1), serving as an indicator that characterizes the quality of the channel.

The SNR value is determined by the satellite beam energy and the Gaussian beam profile, as shown in Eq. (5), which are defined by the design of the spacecraft. We calculate the $\mathrm{BER}_2/\mathrm{BER}_1$ value for the CubeSat Impulse-1 with the payload Vector in low Earth orbit. Let us the SNR_1 value to be at least 13 dB at the at the maximum elevation $\boldsymbol{\alpha} = 85°$, so that the BER is not more than 10^{-6}, according to Eq. (4) (see Fig. 2).

The divergence parameter of a diffraction-limited optical system σ is set to 5 in the zenith position ($\boldsymbol{\alpha} = 0°$), which is typical for optics that can be installed on a spacecraft of such a form factor as CubeSat. Note that the SNR value changes due to the varying distance between the

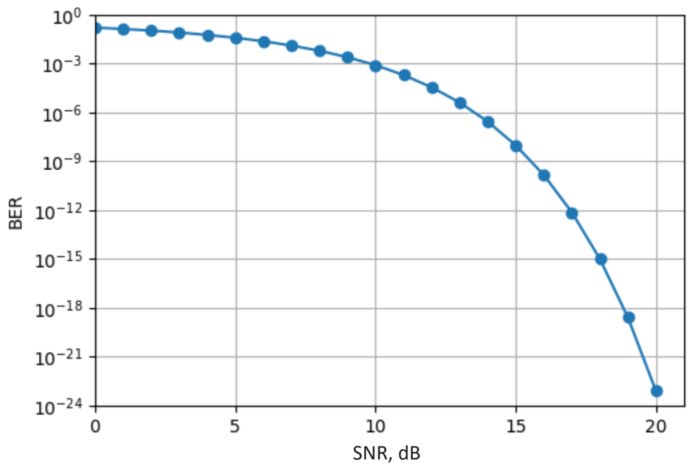

Fig. 2. Bit error rate vs signal-to-noise ratio for PPM coding

satellite and the ground station, and the divergence parameter also changes as the diameter of the Gaussian beam spot on Earth changes. The values can be determined and calculated based on the parameters of the orbit. Fig. 3 illustrates the dependence of the bit error ratio (BER_2/BER_1) on atmospheric refraction, specifically in relation to elevation angle of the satellite along its trajectory.

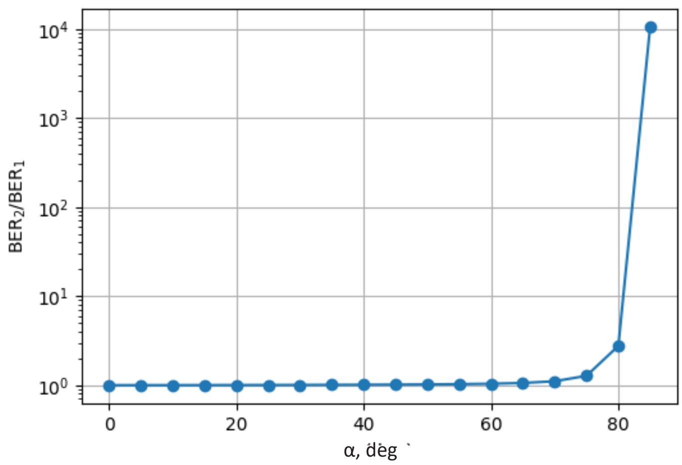

Fig. 3. Bit error ratio (BER_2/BER_1) vs elevation angle for PPM coding

Starting from the elevation angles of more than 60°, the influence of atmospheric refraction on the deterioration of the bit error ratio is emerged. At elevation angles of more than 80°, there is a sharp increase in bit errors by more than 10 dB, which cannot provide the required level of errors. As a result, we should consider atmospheric refraction to optimize the use of the communication channel and maximize the duration of the communication session.

Conclusion

We have conducted the calculations of the increase in the BER as a function of the elevation angle of the spacecraft, taking into account the phenomenon of atmospheric refraction. The changes in the BER due to the contribution of the refraction phenomenon in the atmosphere allow us to assess the quality of the channel in the classical optical communication link between the spacecraft and the Earth. The results of the calculations show that at zenith angles of more than 80 degrees and up to 90 degrees, there is a sharp increase in BER from one to several orders of magnitude, which requires compensation.

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