Study of the dependence of the spatial structure of the optical response of a microsatellite on its speed and orbit height

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Abstract. The paper considers the problem of optical radiation propagation in a passive laser reflector satellite orbiting the Earth, along with reflected signal formation at the earth surface. In these conditions, the optical system will be significantly affected by moving media optics, which may interfere with the possibility of receiving the signal reflected by the satellite. The paper aims to develop a mathematical simulation taking into account the effects of moving media optics and track the spatiotemporal structure of the signal as a function of the optical system velocity.

1. Introduction
In the future, calibration of aerospace laser ranging systems will involve launching passive laser reflector satellites [1]. Such satellites are able to ensure a fundamental level of accuracy in estimating spatiotemporal coordinates of ground and airborne objects. This paper considers the BLITS satellite [2], which is a bi-layer Luneburg lens in a geosynchronous Earth orbit, as a reference. An optical system in these conditions may be used as a laboratory for investigating effects of moving media optics [3].

The aims of the paper are as follows: to verify solutions to the equations of the electrodynamics of moving media in three dimensions; to establish whether the distribution of reflected radiation intensity is a function of satellite velocity and orbital altitude, which should make it possible to assess the degree to which effects of moving media optics affect the possibility of using the BLITS and BLITS-M satellites to calibrate laser ranging systems.

2. Mathematical model
Let us consider the main steps for solving the problem of shaping the optical response in a moving heterogeneous optical system:

1) The first step involves solving a kinematic equation system [4] (1), which, for two dimensions, consists of the following: a second-order curve equation; equations taking into account spatial displacement of the optical surface as the light beam propagates in the system \((t + T)\); light beam propagation equations. If the lens is rotating, it is necessary to account for deviation in the light beam propagation trajectory, meaning that the system (1) requires an iterative solution that accounts for variation in the beam trajectory through the equation
describing its curvature in a non-uniformly moving medium [5] (2):

\[
\begin{pmatrix}
    a_{11} X^2 + a_{22} Y^2 + 2a_{12} XY + 2a_{13} X + 2a_{23} Y + a_{33}
\end{pmatrix} = 0
\]

\[
X = x + \nu_x(t + T), \quad Y = y + \nu_y(t + T)
\]

\[
x = x_{i-1} + l_{i-1} t, \quad y = y_{i-1} + m_{i-1} t
\]

\[
K = \frac{\sin(\theta_2) \cos(\theta_2) \partial k_{2z}}{k_2} = \frac{k_{2z} k_{2z}}{(k_{2z}^2 + k_{2}^2)^{3/2}} \partial k_{2z}
\]

2) When electromagnetic radiation propagates in a non-uniformly moving medium, it is also necessary to take rotary polarization into account [6], which may ultimately affect the intensity distribution in the reflected signal. In order to account for this phenomenon, let us use the equation (2), where \( \theta \) is the rotation angle of the polarisation plane, \( \vec{\pi} \) is the unit Poynting vector:

\[
\theta = \int Ads, \quad A = \frac{\varepsilon \mu - 1}{cn} \left\{ (\text{rot}(\vec{\pi}))_z - \frac{1}{2}(\vec{\pi}, \text{rot}(\vec{\pi})) \right\}
\]

3) The second step is solving the problem at the interface between two media [7]; in order to obtain new radiation parameters beyond the interface, a dispersion equation is solved [8] (2), where \( \beta = u/c, \kappa = \varepsilon \mu - 1 \). The system (3) is solved to account for variation in magnitudes and the rotation of the polarisation plane:

\[
\vec{k}_i^2 - \frac{\omega^2}{c^2} \frac{\kappa_i}{1 - \beta_i^2} \left( \omega - \vec{k}_i \vec{u}_i \right)^2 = 0
\]

\[
E_{2y} = \frac{2k_{0z}}{k_{0z} + k_{2z}} \left\{ 1 + \frac{\kappa \beta_2^2}{1 - \beta_2^2} \frac{k_{0z}}{k_{0z} + \kappa_0 z + (n+1)k_{0z}} \right\} E_{0y}
\]

\[
E_{1x} = E_{2x} = \frac{\kappa \beta_2^2 (\beta - \omega/c_{0z})}{1 - \beta_2^2} \frac{k_{0z}}{k_{0z} + \kappa_0 z + (n+1)k_{0z}} E_{0y}
\]

\[
E_{0x} = 0
\]

4) The final step is deriving the intensity distribution by computing the interference [9]; specifying a uniform grid along the Ox axis, we obtain phases and magnitudes at the recording surface for a set of \( n \) beams in sequence, using the equations from the system (4); as a result, we obtain the intensity as a function of the coordinate (5):

\[
\begin{align*}
A_{res}(x) &= \sqrt{A_{res}(x)^2 + A_i^2 + 2A_{res} A_i \cos(\Phi_{res} - \Phi_i)} \\
\Phi_{res} &= \Phi_{res} + \Phi_i \\
\Phi_i &= \sum_{j=1}^{M} \omega_{i,j} t_{i,j} - \omega_{i,M} \Delta t_i - \sum_{j=1}^{M} k_{i,j} r_{i,j}
\end{align*}
\]

\[
I(x) = \frac{c (A_{res}(x) \cos(\Phi_{res}))^2}{8\pi}
\]

3. Computation results

Our numerical experiment concerned the BLITS-M satellite with the following parameters: number of beams: \( N = 10^5 \), wavelength: \( \lambda = 532 \text{ nm} \), central beam intensity: \( dI = 5 \cdot 10^{-7} \text{ W/m}^2 \); we assumed the beam intensity to be a Gaussian function of the coordinate of the beam/lens intersection point, with a standard deviation of \( \sigma = 8 \cdot 10^{-4} \); incidence angles: \( \theta = 0...3^\circ \); phase summation interval: \( d\theta = 0.5 \text{ arcsecond} \).

The computations were conducted in the Fresnel/Fraunhofer zone modes (10 m/1500 m, respectively), for the cases of both accounting and not accounting for the satellite orbital velocity (the linear satellite velocity being 7100 m/s).
Figure 1. a) Radiation pattern for the BLITS-M satellite as recorded using a measuring bench $V = 0$ m/s b) Radiation pattern obtained in the numerical experiment not accounting for velocity in the Fresnel zone (the recording surface is located at a distance of 10 m from the centre of the lens).

Figure 2. Radiation pattern obtained in the numerical experiment accounting for the satellite velocity of $V = 7100$ m/s. a) Fresnel zone (the recording surface is located at a distance of 10 m from the centre of the lens). b) Fraunhofer zone (the recording surface is located at a distance of 1500 km from the centre of the lens).

Figure 3. Satellite velocity and orbital altitude as functions of a) Deflection angle of the lateral spike in the intensity maximum b) Intensity in the reception region.
4. Conclusion
The functions obtained for reflected signal intensity distribution enable us to draw the conclusion that computation is fundamentally different in the Fresnel and Fraunhofer zones (Figure 2). Velocity also affects beam redistribution at the recording surface, which contributes to intensity spike displacement and variation in the signal-to-noise ratio in the reception region (Figure 3). The data obtained means that the effects of moving media optics impact the potential of a laser ranging system in the case of the BLITS-M satellite; these results may be used to solve the inverse problem of reshaping the lens geometry or varying its velocity and orbital altitude to achieve optimum signal level in the reception region.

References
[1] Shargorodsky V D, Sadovnikov M A 2013 Laser Glonass Bulletin of the Reshetnev Siberian State University of Science and Technology 6 p 52 (in Russian)
[2] Kucharski D, Kirchner G, Hyung-Chul Lim and Koidl F 2011 Adv. Space Res. 48 pp 1335–40
[3] Gladyshev V O and Tereshin A A 2016 Luneburg Lens in the moving coordinate system Optics and Spectroscopy 120 5 pp 822-30 (in Russian)
[4] Gladyshev V O, Tereshin A A, Yavorskiy A V and Bazleva D D 2015 The propagation of monochromatic electromagnetic radiation inside of luneburg lens in relative coordinate frame of reference 5th International Workshop on Computer Science and Engineering: Information Processing and Control Engineering
[5] Gladyshev V O, Bazleva D D, Tereshin A A and Gladysheva T M 2016 Evaluation of the effect of the curvature of the light beam in a rotating Luneburg lens JETP Letters 42 18 pp 39-45 (in Russian)
[6] Rozanov N N and Sochilin G B 2006 Relativistic effects of the first order in the electrodynamics of media with inhomogeneous velocity Physics-Uspekhi 176 pp 421-39 (in Russian)
[7] Gladyshev V O and Strunin A G 2017 The interference response of space microsatellite having the form of the Luneburg lens Journal of Physics: Conf. Series 918 012045
[8] Bolotovsky B M and Stolyarov S N 1989 Reflection of light from a moving mirror and related tasks Physics-Uspekhi 159 1 pp 813-83 (in Russian)
[9] Gladyshev V O, Strunin A G, Kauts V L, Kayutenko A V and Bazleva D D 2018 Effects of moving media optics in GLONASS optical segment of new generation Journal of Physics Conference Series 1051 012031