The interference response of space microsatellite having the form of the Luneberg lens

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Abstract. The calculations were performed for "Blitz" satellite parameters. Luneberg lens consisted of a central sphere of radius \( R_2 = 53.5 \) mm and an external meniscus of radius \( R_1 = 85 \) mm, with half of the external meniscus having a mirror coating. Central sphere was made of heavy flint glass with a refractive index \( n_2 = 1.76470 \), and an external meniscus was made of light crown glass with a refractive index \( n_1 = 1.47290 \), the laser wavelength was \( \lambda = 532 \) nm. The speed of the lens moving in its orbit was 7500 m/s, the orbit height was \( h = 835 \) km.

The task of increasing the accuracy of global satellite positioning systems can be solved with an optical segment which is, in general, a set of reference LEO satellites with a set of reflectors.

In [1] it is shown that spherical gradient-index Luneberg lens can be used as a microsatellite-reflector. The satellite optical response is comparable to the response of a point source and can be used to improve the accuracy of coordinated determining in the GLONASS system.

The theoretical model of the optical response formation by the moving Luneberg lens must include the equation of moving media electrodynamics. This is because there is the additional ray deflecting and stirring in the rotating lens moving in the orbit [2, 3]. The result is a redistribution of the intensity of radiation reflected by the satellite "Blitz", in the recording plane on the Earth's surface.

The multipath interference response of Luneberg lens moving in the Earth's orbit is calculated in the work, with due account for the effects of the moving media electrodynamics.

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The intensity distribution of the reflected radiation on the Earth's surface was found depending on coordinates for the lens central aperture.

The calculation of parameters of the radiation passing through the moving medium is based on the dispersion equation

\[
\frac{k^2}{c^2} - \frac{\omega^2}{c^2} - \left( \frac{\epsilon \mu - 1}{c^2} \right) \cdot \left( \frac{\omega^2 - k^2 c^2}{1 - u^2/c^2} \right) = 0.
\]

(1)

Solving the equation allows us to determine the wave vector projections and frequencies at all sections of the light ray trajectory from the radiation source to the receiver.
The theoretical model, following [2], uses the kinematic equations for the rays in geometric approximation.

To calculate the intensity distribution in the plane of the signal reception, angular deflection of the beam reflected by the satellite, $\Delta \theta$, was introduced. Then, the beam deflection relative to the terrestrial detector, located near the source of radiation, after reflection by Luneburg lens is equal to

$$\Delta l_j = h t g \Delta \theta_j.$$  \hfill (2)

For phase of $j$-th beam on the Earth's surface it can be written

$$\Phi_j(x) = \sum_{i=1}^{n} w_{ij} t_{ij} - w_b \Delta t_j - \sum_{i=1}^{n} k_{ij} \Delta r_{ij},$$  \hfill (3)

where $\omega_j, t_{ij}, k_{ij}, \Delta r_{ij}$ are the frequency, the propagation time of $j$-th beam, the wave vector module and the length of geometric path at i section of the trajectory respectively, $i = 1..n$, where $n = 8$ is the number of sections in the optical path in the optical system under test between interface boundaries, $\Delta t_j = t_0 - \sum_{i=1}^{n} t_{ij}$ is the difference in transit time of the reference beam and calculated one.

The intensity distribution in the observation plane of the interference pattern depends on the number of rays (from the total number $N$), falling in each coordinate interval (for this task the interval was chosen to be $\Delta x = 1$ m).

$$I(x) = I_0 \left( \sum_{i=1}^{N} \sin \Phi_j(x) \right)^2,$$  \hfill (4)

where $I_0$ is single beam intensity of the order of $10^{-6}$ W/m$^2$.

Numerical calculations were performed with $N = 20000$, in the range of angles of beam incidence on the lens surface $\theta_0 = 0..7^\circ$. The graph of the reflected light intensity distribution $I(x)$ at the Earth's surface is shown in Figure 1.
Figure 1. The dependence of the intensity $I(x)$ of the reflected radiation on the coordinates on the Earth’s surface.

To analyze the dependence of the coordinates of the maximum intensity on the satellite velocity, the coordinate of the maximum intensity of the reflected radiation, $x_m$, is introduced. The graph of the coordinate $x_m$ vs. the satellite velocity $V$ is shown in Figure 2.

Figure 2. The graph of intensity peak coordinates $x_m$ vs. the satellite speed $V$. 
For correction of the form of the intensity distribution (intensity peak shift to the receiving area), it is possible to change the optical system geometrical characteristics. Below the results of calculations of $x_m$ at different radii $R$ of the external satellite meniscus are shown.

**Figure 3.** The dependence of intensity peak coordinates $x_m$ vs. changes in the radius of the meniscus $dR$.

As a result, for $x_m = 0$ $dR \approx 0.64$mm. The graph of the radiation intensity distribution at the external meniscus radius of 85.64 mm is shown in Figure 4.
Figure 4. The light intensity distribution at the outer meniscus radius of the $R_1 = 85.64$ mm.

From the above graph it follows that the change in the outer radius of the meniscus can significantly affect the intensity distribution in the reception area and makes it possible to optimize the signal; so when the radius of meniscus is increased by $dR = 0.66$ mm, the signal strength in the reception area increases by more than 6 times.

As a result of the calculation, the dependence of the radiation intensity in the observation plane of the multipath interference pattern on the satellite velocity was found. Moreover, the inverse problem of finding the dependence of intensity peak coordinates on the lens outer meniscus radius has been solved.

Findings of the research show that a decrease in signal strength due to the presence of satellite motion velocity can be compensated by changing the radius of the lens external meniscus, which will provide an effective signal/noise ratio in the reflected radiation registration area.

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References
[1] Kucharski D, Kirchner G, Hyung-ChulLim, KoidlF2011Adv. Space Res.48 pp 1335–1340
[2] Gladyshev V O, Tereshin A A 2016 A Luneburg Lens in moving Coordinates. Optics and Spectroscopy 120 no. 5 pp 773–780
[3] Gladyshev V O, Bazleva D D, Tereshin A A, Gladysheva T M 2016 Determination of Light Beam Curvature in a Rotating Luneburg Lens. Technical Physics Letters 42 no. 9 pp 948–950
[4] Shargorodsky V D, Vasiliev V P, Belov M S, Gashkin I S, Parkhomenko N N 2006 Spherical Glass Target Microsatellite. *Proceedings of 15th International Workshop on Laser Ranging* pp 566-570