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Ring retroreflector system consisting of cube-corner reflectors with special coating

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Abstract. **The ring retroreflector system (RS) consisting of cube-corner reflectors (CCRs) with a special coating of reflecting surfaces, intended for uniaxially Earth-oriented navigation satellites, is considered. The error of distance measurement caused by both the laser pulse delay in the CCR and its spatial position (CCR configuration) is studied. It is shown that the ring RS, formed by the CCR with a double-spot radiation pattern, allows the distance measurement error to be essentially reduced.**

Keywords: *cube-corner reflector, ring retroreflector system, radiation pattern, diffraction pattern, interference dielectric coating.*

1. Introduction

All modern navigation and geodesic space vehicles (SVs) carry panels of corner reflectors (CCRs), i.e., the so-called retroreflector systems (RSs) [1–6]. These systems are used to reflect the beam of the laser range finder intended for high-precision measurement of the distance to the SV with the aim of correcting the orbit parameters and the refinement of the optical laser station coordinates, as well as calibrating the surface-based measuring radio aids.

Three types of retroreflector systems exist. The first type includes spherical RSs, i.e., collections of CCRs located at the surface of heavy metal spherical satellites, intended for the calibration of laser range finders, as well as for the investigation of the Earth's geopotential (Etalon SVs, Larets, Lares, Lageos, etc). The second type includes the plane CCR panels that are installed at such satellites as GLONASS, Galileo, etc. The number of CCRs in such a retroreflector system is determined by the compromise between the necessary reflection coefficient and the permissible weight of the system on board of the SV. To make the distance measurement more precise they try to use symmetric panels. In this case the CCRs should be arranged in a compact way around the line, connecting the SV centre of gravity with the centre of the Earth. And, finally, the third type includes glass spherical satellites acting as a single lens reflector (Blits) [7].

As is known, a laser range finder measures the short (up to 10 ps) laser pulse propagation time τ_{meas} which is a sum of the times of pulse propagation through the atmosphere, through the free space and within the particular CCR.

At present the international network of laser stations makes use mainly of the laser range finders operating in the so-called single-electron mode, the pulse repetition rate being able to achieve 10 kHz [3, 4]. This fact means that the system is able to receive not greater than one photon of reflected radiation from each pulse of the laser. Provided that the small interference and quantum effects are neglected, the given photon comes from a certain CCR of the panel. Since in the general case the CCRs in the RS are located at different distances from the receiver, the distances being dependent on the light incidence angle, the times of arrival of different signal photons do not coincide.

In the reception path of the laser range finder the signal photoelectrons from the collection of received pulses are 'stored' in the similar temporal cells with the time shift of the pulses taken into account. A collection of photoelectrons stored during the measurement time that includes more than a thousand of pulses, forms the response continuous signal with the measured parameters, namely, the position of the so-called centre of gravity (mathematical expectation) on the time axis, duration [root-mean-square (rms) deviation], etc.

The main goal of ranging is to determine the distance to the SV centre of gravity by analysing and processing the obtained signal. For this purpose it is necessary to take into account the delay of the laser pulse in the CCR, the shape distortion and centre of gravity displacement of the response pulse, as well as the refraction correction.

The goal of the present work is to analyse the precision characteristics of the ring retroreflector systems (RRSs). The specific feature of these systems is that the CCRs are placed within a ring, the central part of the RRS being free of reflectors. Provided that the specially designed reflectors are used, the RRS allows reduction of the ranging error.

2. Calculation of the distance to the chosen point of a particular reflector

Any retroreflector system is characterised by a systematic error, which will be understood as the displacement of the response pulse centre of gravity (mathematical expectation) and the rms, characterising the pulse broadening. The rms is determined by different delays of the laser pulse reflected from CCR in a RS with definite dimensions and symmetry.

The systematic error is determined by the delay of the laser pulse in a particular CCR and any kinds of asymmetry of the RS parameters, e.g., the difference in polarisation characteristics of particular segments of the RS. Besides it is necessary to account for the fact that the spatial point for which the

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distance is calculated does not coincide with the geometric coordinates of the satellite centre of mass that varies in the process of motion.

In laser ranging it is common to characterise the energy potential of a single CCR, as well as that of the entire RS, by the equivalent scattering surface (ESS) which for navigation satellites must be no less than 60×10^8 m^2. This allows the distance determination with the single-measurement rms not exceeding 1 cm at orbits ~20000 km high within the tilt angle range greater than 30° for the atmosphere transmission coefficient 0.7 in the zenith and the precision of the SV orientation towards the Earth centre no worse than ±0.5°.

The systematic error caused by the pulse delay in the CCR may be calculated provided that the values of the tilt angle and the azimuth of SV are known; therefore, it is in fact a correction taken into account in the distance calculation. At least two equivalent methods of taking it into account exist. One of them is based on the concept of the cross section, i.e., the plane that could be reached by the pulse phase front during the total propagation time, divided by two. If the position of this plane depending on the incidence angle is known, one can calculate the distance to the SV centre of gravity. The other approach consists in calculating the correction to the value of the distance to some chosen base point of the SV and then recalculating (reducing) this value to the centre of gravity.

Let us consider both these methods. First let us derive the formula that determines the time of pulse propagation from the laser range meter to the base point S of a particular CCR. This value is the measured time interval between the centres of gravity of the transmitted and received pulses, i.e., between the mathematical expectations of the temporal distributions of the received photons for these pulses. In this case we shall not analyse the corrections related to the pulse delay in the atmosphere [1] and the signal distortions in the photodetector device [8].

Consider a particular CCR with the vertex S being the point the optical path to which determines the measurement time τ_{meas} (Fig. 1). Assume that the impulse function of such a CCR is a delta-function, i.e., the shape and duration of the laser pulse in a single CCR are not distorted.

The angle of incidence θ_{i} of the rays, forming the plane wave from the laser transducer, vary from zero (normal incidence onto the input face of the CCR) to ~13°. Let us express the distance Z_S from the laser transducer to point S in terms of the pulse propagation time

$$\tau_{\text{meas}} = 2\tau_A + 2\tau_{AS}, \quad (1)$$

where τ_A is the time of the ray propagation to point A; τ_{AS} is the time of the ray propagation between points A and S.

Let us denote the time of pulse propagation to point S in vacuum by τ_S. The true distance sought for is

$$Z_S = \tau_S c = Z_N + h\cos\theta_{\text{i}}, \quad (2)$$

where Z_N is the true geometric distance of point N. Let us relate this quantity to τ_{meas}.

The distance between points A and S is $Z_{AS} = h/\cos\theta_{\text{t}}$, where θ_{t} is the angle of refraction, and h is CCR height. The optical path of the ray inside the CCR depends on the incidence angle and the refractive index of the CCR material as $\Delta_{AS} = nh/\cos\theta_{\text{t}}$. Note that one should account for the effects related to the difference between the phase and the group velocity in the CCR material.

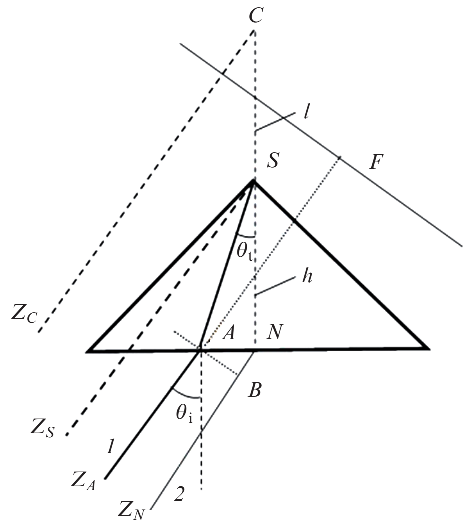

Figure 1. Scheme of distance measurement using a single CCR: S is the CCR point, the optical path length to which is equal to the optical path length of all beams that enter the CCR aperture; A is the entrance point of the ray, arriving at point S; N is the foot of the perpendicular, dropped from point S; $SN = h$ is the geometrical height of the CCR; C is the point to which the distance is to be calculated; F is the cross section; *1*, *2* are the rays coming from the laser transmitter.

Multiplying both sides of Eqn (1) by the velocity of light and dividing by two we get the distance Z_A of point A, equal to the difference between $\tau_{\text{meas}}c/2$ and the optical path length of the principal ray inside the CCR

$$Z_A = \tau_{\text{meas}}c/2 - \Delta_{AS} = \tau_{\text{meas}}c/2 - hn/\cos\theta_{\text{t}}. \quad (3)$$

The distance Z_N of point N differs from the distance Z_A of point A by the length of the segment $BN = \Delta_{BN}$, where point B is the foot of the perpendicular dropped from point A on ray 2:

$$Z_N = Z_A + \Delta_{BN} = \tau_{\text{meas}}c/2 - \Delta_{AS} + \Delta_{BN}.$$

Since $AN = h\tan\theta_{\text{t}}$, we find than

$$\Delta_{BN} = AN\sin\theta_{\text{i}} = h\tan\theta_{\text{t}}\sin\theta_{\text{i}} = h\frac{\sin^2\theta_{\text{i}}}{n\cos\theta_{\text{t}}}.$$

After simple transformations we get

$$-\Delta_{AS} + \Delta_{BN} = -\frac{hn}{\cos\theta_{\text{t}}} + h\frac{\sin^2\theta_{\text{i}}}{n\cos\theta_{\text{t}}} = -\frac{h(n^2 - \sin^2\theta_{\text{i}})}{n\cos\theta_{\text{t}}}$$

$$= -h\sqrt{n^2 - \sin^2\theta_{\text{i}}}, \quad (4)$$

$$Z_N = \tau_{\text{meas}}c/2 - h\sqrt{n^2 - \sin^2\theta_{\text{i}}}.$$

From Eqn (2) with Eqn (4) taken into account we obtain the sought-for true distance of point S

$$Z_S = \tau_{\text{meas}}/2 + h\cos\theta_{\text{i}} - h\sqrt{n^2 - \sin^2\theta_{\text{i}}}. \quad (5)$$

For the time of pulse propagation to point S the following formula can be written:

$$\tau_S = \tau_{\text{meas}}c/2 + (h\cos\theta_{\text{i}} - h\sqrt{n^2 - \sin^2\theta_{\text{i}}})/c. \qquad (6)$$

The difference between $\tau_{\text{meas}}/2$ and τ_S determines the systematic error of the sought-for time of pulse propagation to base point S, introduced by the particular CCR

$$\Delta\tau_S = h(-\cos\theta_{\text{i}} + \sqrt{n^2 - \sin^2\theta_{\text{i}}})/c, \qquad (7)$$

and the systematic error of the corresponding calculated distance

$$\Delta_S = \tau_{\text{meas}}c/2 - Z_S = h\sqrt{n^2 - \sin^2\theta_{\text{i}}} - h\cos\theta_{\text{i}}. \qquad (8)$$

The distance from point N at the input face of the CCR to the cross section is

$$NF = \tau_{\text{meas}}c/2 - Z_N = h\sqrt{n^2 - \sin^2\theta_{\text{i}}}. \qquad (9)$$

3. Calculation of the RS base point distance

Let it be necessary to relate the SV distance measurement to auxiliary point C, given at the landing plane of the RS (see Fig. 1). Obviously, the geometric path length to any spatial point, including point C, can be determined from the vector relation

$$\boldsymbol{Z}_C = \boldsymbol{Z}_S + \boldsymbol{L}_{SC}. \qquad (10)$$

Here the vectors $\boldsymbol{Z}_C$ and $\boldsymbol{Z}_S$ are directed from the laser transducer to points C and S, respectively; the vector $\boldsymbol{L}_{SC}$ is directed from point S to point C; and $|\boldsymbol{L}_{SC}| = l$ is the distance from point S to point C. To calculate $|\boldsymbol{Z}_C|$ it is necessary to define the coordinate system, bound to the RS.

In the simplest case when point C is located at the perpendicular NS, we get the true value of the distance to this point

$$Z_C = Z_S + l\cos\theta_{\text{i}} = \tau_{\text{meas}}c/2 - \Delta_S + l\cos\theta_{\text{i}},$$

from where the formula for the correction to the calculation of distance to point C follows

$$\Delta_C = Z_C - \tau_{\text{meas}}c/2 = -\Delta_S + l\cos\theta_{\text{i}} = (h + l)\cos\theta_{\text{i}} - h\sqrt{n^2 - \sin^2\theta_{\text{i}}}. \qquad (11)$$

This value must be added to the measured value of the distance $\tau_{\text{meas}}/2$. Let us perform numerical estimation of the quantity Δ_C for h = 19.1 mm and l = 25.9 mm. The dependence of Δ_C on the incidence angle θ_{i} is presented in Fig. 2, from which it follows that the variation of the systematic error does not exceed 1 mm, and its mean value amounts to ~16.2 mm.

In the general case the vector $\boldsymbol{L}_{SC}$ is determined by the RS construction and is defined in the instrumental coordinate system, bound to the satellite. In the same coordinate system the transition from point C to the satellite centre of gravity can be performed. In this case the change in the centre of gravity position in the process of the SV flight should be taken into account.

Let us calculate the distance L_{CF} from point C of the landing plane of the RS to the cross section. It is obvious that

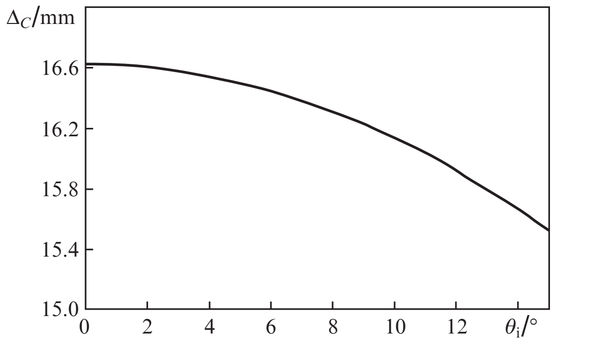

Figure 2. Dependence of the systematic correction to distance to point C on the angle of light incidence on the RS.

$$L_{CF} = Z_C - \tau_{\text{meas}}c/2 = (h + l)\cos\theta_{\text{i}} - h\sqrt{n^2 - \sin^2\theta_{\text{i}}}. \qquad (12)$$

From the comparison of Eqn (12) and Eqn (11) it follows that L_{CF} is exactly equal to the systematic correction Δ_C in the calculation of distance to point C. This means identity of the considered above methods of correcting the 'measured' using a single CCR.

4. Correction of systematic and random errors of the pulse propagation time measurements, caused by the size and configuration of the RS

Let us consider the errors caused by the joint operation of CCRs in the RS. When a symmetric probe pulse is reflected from the RS in the general case the pulse is elongated, together with the distortion of its symmetry and the shift of its centre of gravity [8, 9]. We restrict our studies to three types of plane symmetric RSs, namely, the rectangular panel, the ring RS with uncoated CCRs, and the RS with the so-called double-spot CCR of increased size (Fig. 3). Let us compare the distortions of the signal by these RSs in application to the satellite-based laser rangers, in which the single-electron mode of response pulse reception is used.

Let us carry out approximate analysis, assuming that a single CCR does not distort the laser pulse, but only delays it according to Eqn (70), and the pulses reflected from CCRs are incoherent, i.e., their intensities are additive without taking the phase relations into account. In this case it is necessary to account only for the individual displacements of the pulse along the temporal axis, introduced by each CCR. Assume that the zero individual displacement is attributed to the pulse reflected from the CCR located in the panel centre of symmetry.

We define the coordinate system xyz with the origin at the symmetry centre of the RS, the axes x and y lying in the plane that passes through the vortexes S_i of all CCRs, and the axis z directed perpendicular to this plane (see Fig. 3). For the ring RS we will also use the polar coordinate system (r, ψ).

Each CCR in both cases is characterised by the vector $\boldsymbol{r}$ lying in the plane and directed from the origin to point S_i. The pulse delay time for the given CCR (with the sign both plus and minus) is determined by the projection of $\boldsymbol{r}$ onto the sight line, i.e., the vector $\boldsymbol{R}$ directed from the laser transducer to the centre of the RS symmetry. Let us define this vector in the system xyz by the angles θ_{i} (the angle of incidence) and φ (the azimuthal angle). Let us denote by α_i the angle between the

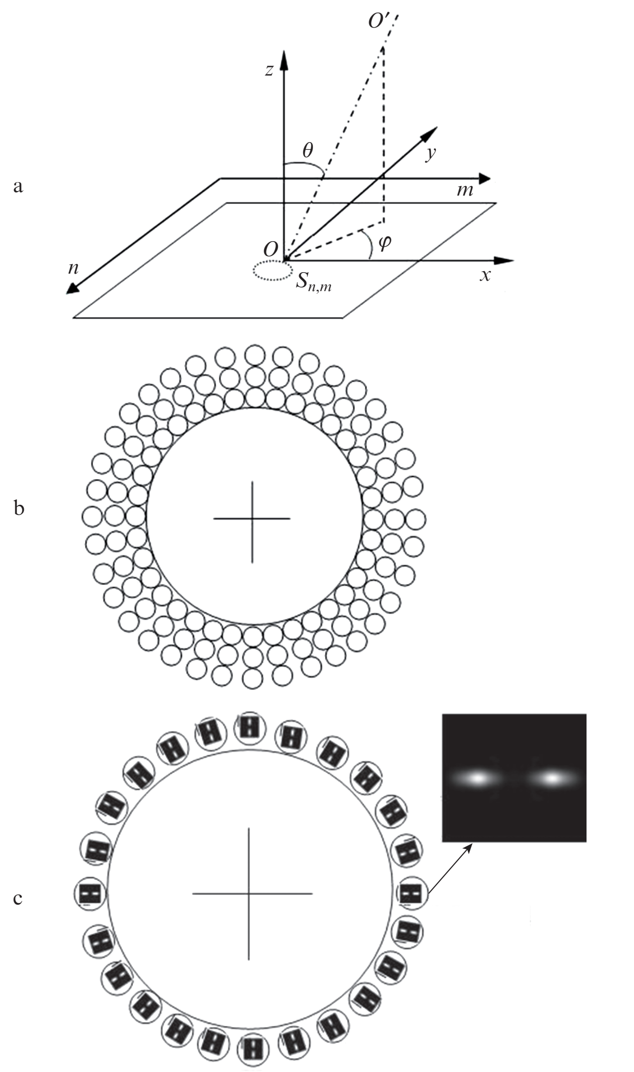

Figure 3. Types of reflector systems: (a) planar rectangular panel, (b) ring retroreflector system (RRS) formed by uncoated CCRs, and (c) the RRS consisting of double-spot CCRs. It is shown how the radiation patterns for each CCR are oriented.

vectors $\boldsymbol{r}_i$ (r_x, r_y, 0) and $R(\sin\theta\cos\varphi, \sin\theta\sin\varphi, \cos\theta)$, then the projection of $\boldsymbol{r}_i$ onto $\boldsymbol{R}$ expressed as $|r_i|\cos\alpha_i, = r_x\sin\theta\cos\varphi + r_y\sin\theta\sin\varphi$, and the corresponding time delay is $\Delta\tau_i = |r_i|\cos\alpha_i/c$.

Consider first the plane panel consisting of 117 CCRs, 13 rows parallel to the x axis and 9 rows parallel to the y axis. Each CCR is labelled by two subscripts, characterising its location in the panel, m along the x axis and n along the y axis. The zero values of x and y correspond to the CCR located in the panel centre. Let the distance d between points S_i of the CCR equal, e.g., 50 mm (similar along the axes x and y). Then for the time delay of the pulse, reflected from the CCR with the coordinates m, n, with Eqn (7) taken into account, we get the following expression:

$$\Delta\tau_{mn} = \frac{d}{c}\sin\theta(m\cos\varphi + n\sin\varphi) + \Delta\tau_S. \tag{13}$$

Using Eqn (13), let us determine the intensity of a single reflected laser pulse in the form of the Gaussian function with the width 2τ at the level of 1/e of the maximal value

$$I_{mn}(t) = \frac{1}{\sqrt{\pi}\,\tau}\exp\left[\frac{-(t-\Delta\tau_{mn})^2}{\tau^2}\right]. \tag{14}$$

The total reflected pulse is expressed as the sum of all $I_{mn}(t)$:

$$I(t) = \sum_{m=-4}^{4}\sum_{n=-6}^{6} I_{mn}(t). \tag{15}$$

The result of summation is shown in Fig. 4 for different values of the angles φ and θ and for different duration of the pulses 2τ. If the projection of the laser beam at the panel is not parallel to the axis x or y ($\varphi \neq 0, 90°$), then for a short (e.g., 1 ps) incident pulse the reflected pulse has the shape of a trapezium. In the opposite (parallel) case the pulse is rectangular. The broadening of the incident pulse leads to smoothening of this shape. The shortening of the incident pulse duration leads

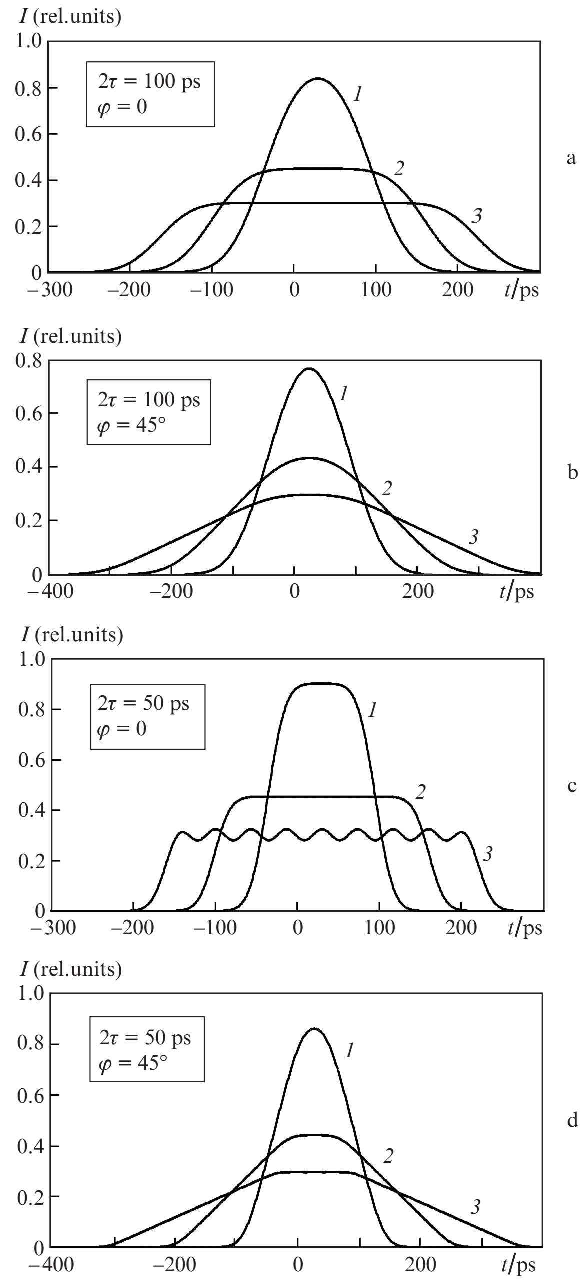

Figure 4. Broadening of Gaussian pulses at different values of 2τ and φ: θ = (*1*) 5°, (*2*) 10° and (*3*) 15°.

to modulation of the reflected pulse, caused by the effect of individual CCRs of the panel.

The centres of gravity of all curves possess similar shift along the temporal axis due to the pulse delay in a single CCR. Therefore, ideally the panel size and the incident ray azimuth do not give rise of ranging error. It is necessary to take only the systematic error correction Eqn (7) into account.

Now consider the RRS consisting of three rows of CCRs with the uncoated faces. As is known, in the case of total internal reflection of light from the CCR faces the diffraction pattern of the reflected radiation in the far zone has one central and six peripheral spots. By special turn of each CCR in the plane of the panel one can obtain the intensity ring, formed by the lateral spots of each CCR. Since the diffraction pattern of the RS is produced by all CCRs, the photons, reflected from all CCRs, arrive at the receiver. Let the RRS consist of three rows of CCRs, 36 pieces in each (see Fig. 3b), where n is the number of the CCR in the ring ($n = 0, 1, \ldots, 35$); m is the number of the row ($m = 0, 1, 2$); and R is the radius of the RRS. Taking the ring symmetry of the RRS into account, one can put $\varphi = 0$ without any loss of generality.

The for the time delay of the pulse reflected from the CCR with the subscripts m and n with Eqn (7) taken into account we get the expression

$$\Delta\tau_{mn} = -\frac{R}{c}\sin\theta\cos\left(\frac{\pi}{18}n\right)(1 + dm) + \Delta\tau_S. \quad (16)$$

The total reflected pulse in this case is found from the expression

$$I(t) = \sum_{m=0}^{2}\sum_{n=0}^{35} I_{mn}(t); \quad (17)$$

it is presented in Fig. 5 for different values of the incidence angle θ and durations of the initial pulses 50 and 100 ps at $R = 230$ mm and $d = 40$ mm.

From Figs 4 and 5 it follows that the centre of gravity of the distribution of the response pulse arrival times is shifted only by the value equal to the delay of the pulse in a single CCR. If the number of responses is large enough, then the mean time of photoelectron appearance in the receiving tract of the laser ranger coincides with the centre of gravity of the response pulse. In other words, the systematic error of measurements (temporal shift) caused by the dimensions of the panel equals zero, and the random error is equal to the root mean square duration of the response pulse. Conservation of the measurement accuracy requires an appropriate increase in the repetition rate of probe pulses. The so-called normal points are obtained by averaging the measurements over the temporal interval 300 s. The rms obtained using the normal point appear to be $\sqrt{N}$ times smaller.

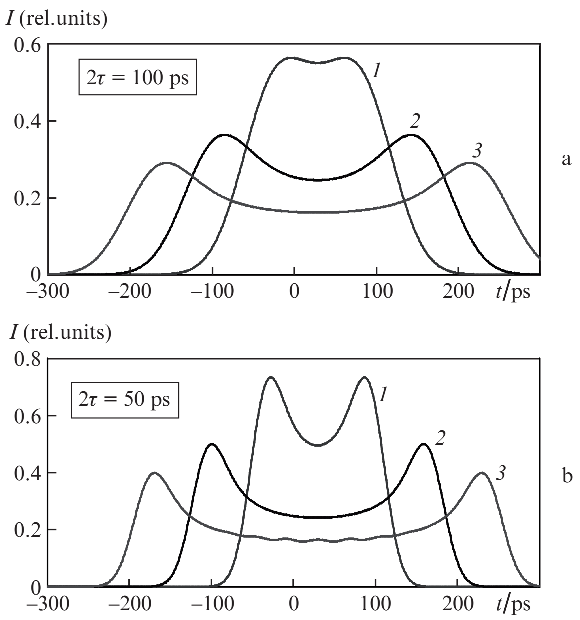

Figure 5. Broadening of Gaussian pulses at different values of 2τ; θ = (*1*) 5°, (*2*) 10° and (*3*) 15°.

Thus, in the single-electron detection mode with the number of measurements $N > 100$ the systematic component of the range measurement error correction loses the dependence on the dimensions of the symmetric RS, but the required accuracy can be achieved only by averaging multiple measurements. Practically, due to the influence of external factors (e.g., weather conditions) the number of measurements may be only 10–20, and then the RMS of a single measurement becomes important.

5. Ring retroreflector system, consisting of double-spot CCRs of increased size

Consider the problem of reducing the single measurement random error upon an increase in the energy of the reflected signal in the direction of the receiver of the laser ranger.

In order to increase the energy they make the ESS larger in the appropriate direction. As is known, the phenomenon of velocity aberration [1] in the process of the space vehicle motion leads to the deviation of the reflected ray in the plane, formed by the SV velocity vector and the sight line. This means that the reflected radiation pattern, or the dependence of the ESS on the angular coordinates, should be adapted to the SV with definite parameters and orbit height. The GLONASS satellites have only uniaxial orientation; therefore, the SV rotates in the plane, orthogonal to the direction towards the Earth. The angular aberration of velocity for these satellites is nearly equal to $\sim 5''$.

One of the promising methods for solving the problem of enlarging the ESS is the use of a ring RS, consisting of double-spot CCRs with greater size. The double-spot diffraction pattern is formed due to the controlled variation in one of the dihedral angles (Fig. 6). The faces of such CCRs should be covered with a special dielectric coating, on the one hand in order to provide the appropriate radiation pattern, and on the other hand, to reduce its thermal distortions.

The optimal radiation pattern is provided by the choice of the CCR size (42–48 mm) and the deviation $2.2''$–$2.5''$ of the angle between the reflecting CCR faces from 90°. If the line connecting the spots also lies in this plane, then for the angular distance between the spots equal to twice the angle aberration one of the spots will hit the receiver of the reflected signal. This allows the energy loss reduction that arises if the diffraction pattern has the form of one or seven spots [6, 10].

However, the reasonability of using the RRS is not reduced to the ESS enlargement. Let us show that in this case it is possible to reduce the rms of a single measurement.

Let the orientation of the RRS be defined by the projection of the edge of the dihedral angle that differs from 90°

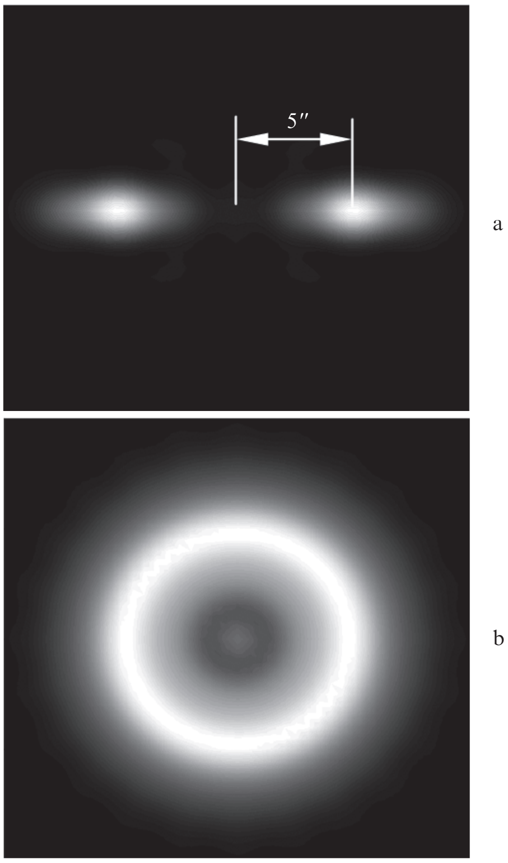

Figure 6. Radiation patterns of (a) the double-spot CCR and (b) of the entire RRS.

onto the plane in which the bases of all CCRs lie. To provide reflection of light in the required direction by at least one CCR, one should rotate all CCRs in the panel by a certain angle with respect to each other; e.g., for 18 CCRs this angle equals 10°. The angular size of each spot with respect to the centre of the diffraction pattern depends on the CCR size: the larger the CCR the smaller this size (for example, for the CCR aperture diameter of 48 mm this is about 30° at half-maximum intensity level). In this way the adjacent spots add to form the ring-shaped diffraction pattern.

The principle of operation for the RRS with turned two-spot CCRs is the following. Consider the hypothetic situation when the tangent component of the SV velocity is zero and the angular aberration is absent. In this case the centre of the ring diffraction pattern at the surface of the Earth coincides with the receiver, and there is no reflected signal. If the satellite moves with the velocity for which the angular aberration equals the angular size of the diffraction pattern, a certain part of the ring overlaps the receiver. This part is formed by one of the two spots from the CCR, definitely oriented in the RS. There can be several such CCRs.

Thus, the signal, reflected in the direction of the laser ranger located on the surface of the Earth is produced not by all CCRs, as, e.g., for the planar panel of uncoated CCRs [6, 10], but by only a few of them, in the ideal case, by two identically oriented CCRs located at the opposite sides of the RRS (see Fig. 3). Using not one but two CCRs with the same orientation, separated by a certain distance, allows the solution of the important problem of reducing the RMS of the single distance measurements.

If 36 CCRs are used in the RRS, each of them being rotated by 10° with respect to the next one from each side of the RRS, then the signals of three adjacent CCRs are added. Generally, the choice of the optimal CCR size and their total number allows obtaining the maximal possible value of the ESS for such RRS independent of the azimuth and tilt angle of the SV observed.

Let us consider the single-measurement errors for two RRSs, consisting of uncoated CCRs (Fig. 5) and of double-spot CCRs (Fig. 7). In the first case the RMS σ of the single measurement is proportional to the panel size. If the signal has the duration 50 ps (at the 1/e level of the maximal value) then depending on the incidence angle θ the following broadening in the temporal scale arises: for $\theta = 5°$, 10° and 15° the RMS is $\sigma = 54$, 103 and 153 ps, respectively (see Fig. 5). With the fact that the delay of the pulse by 10 ps leads to the change in the distance by ~3 mm taken into account, for the rms of the distance single measurement we obtain 16, 31 and 46 mm, respectively. At the signal duration 100 ps the broadening values are 62, 108 and 156 ps.

In the case of the RRS consisting of double-spot CCRs (Fig. 7), in contrast with the planar panel and the RRS with uncoated CCRs, the reflected pulse does not broaden, but splits into two pulses that in the ideal case conserve the initial Gaussian shape. Every rms in determining the centre of gravity of these two signals equals the square root of the sun of their rms squares (provided that the signal photons from the CCRs from both sides of the RS are present). For the duration of the initial pulse 50 ps this is $18\sqrt{2} = 25$ ps, and for the duration 100 ps thi is $35\sqrt{2} = 49$ ps, independent of the angle of incidence. For the angle of incidence $\theta = 15°$ and the pulse duration 50 ps the rms for double-spot CCRs with the aper-

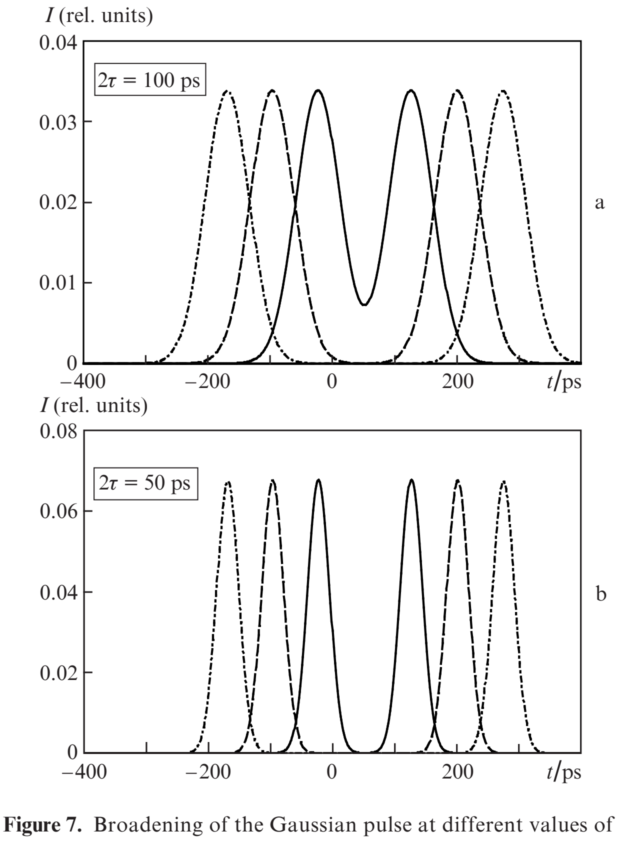

Figure 7. Broadening of the Gaussian pulse at different values of 2τ; $\theta = 5°$ (solid curve), 10° (dashed line) and 15° (dot-dashed line).

ture 48 mm is six times smaller than the rms for the uncoated CCRs with the aperture 28 mm.

6. Conclusions

The systematic error in measuring the distance to symmetric retroreflector systems by means of a laser ranger is determined by the delay of the laser pulse in a single corner reflector. At the same time the rms of single distance measurement is determined by the RS dimensions and CCR arrangement, as well as, generally, the CCR parameters, namely, the dimensions, the angles between the CCR faces, the type of the face coating. The single-measurement rms is reduced if the ring retroreflector system is formed by double-spot enlarged CCRs. In this case the diffraction pattern is formed at the expense of the specified angle between the two reflecting faces and the special interference coating of the faces, providing a definite phase shift of the orthogonal components of the electric vector in the process of reflection. Theoretically the rms can be reduced by several times using the CCRs with the aperture of 42–48 mm and the deviation of the dihedral angle by 2.4″. The advantage of such RRS is realised using short probe pulses (to 100 ps) and large angles of incidence of light onto the RRS (greater than 5°).

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