ESTIMATION OF THE SLANT RANGE MEASURED WITH A SPACEBORNE "BALKAN" LIDAR FROM THE SPACE STATION "MIR"

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We consider some peculiarities in ranging with a space-based lidar "Balkan" of the ocean surface for two modes of the space station "Mir" orientation used during lidar measurement sessions. We have analyzed regular and random fluctuations of the lidar optical axis position in space that occurred in these sessions. An estimate of possible causes of the systematic difference between the ballistic calculated data on range and the values of slant range measured with the lidar in both modes of the station orientation is made.

INTRODUCTION

Possible errors in ranging with space-based laser altimeters were previously considered in Ref. 1. Some preliminary results on ranging of the Earth surface performed with a space-based lidar "Balkan" we have presented in our earlier papers.$^{2-4}$

In this paper we consider some peculiarities in ranging the ocean surface with a space-based lidar "Balkan" for two modes of the "Mir" space station orientation used during lidar measurement sessions in 1995-1996.^{2,3,5} In the routine mode of the "Mir" station orientation, called ICS2 (inertial coordinate system 2), when the space station-fixed coordinate system was oriented with respect to the basic inertial coordinate system, an angle between the lidar optical axis and nadir direction, γ, continuously changes thus causing also continuos variation of the slant range, D (Fig. 1*a*). On the illuminated side of the Earth this angle changed in the limits $-90° \le \gamma \le +90°$ and on the dark side the angle γ always exceeded 90°. Thus, the Earth ranging (in the lidar operation limits) was feasible only on the illuminated side, at the illumination peak, when the lidar optical axis was directed close to nadir direction.

When the space station was operated in the mode of calculated orbital orientation, called orbital coordinate system (OCSc), it was oriented in such a way that the lidar optical axis was always looking at nadir. Such an orientation allows one to carry out the measurement sessions both on illuminated and dark sides of the Earth (Fig. 1*b*). If the lidar optical axis is kept looking exactly at nadir during measurement session, the measured value D_m should be equal to the calculated orbit height H_c.

The instrumental error of ranging with the range finder channel of the "Balkan" lidar is ±1.5 m.^{6} We estimate possible causes of differences between calculated D_c and measured D_m values of the slant range based on data of lidar sensing of the ocean surface, telemetric information from space station, and calculated ballistic data.

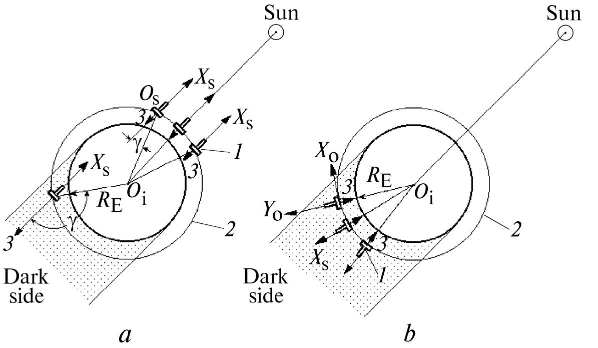

FIG. 1. Schematic picture of the orientation modes of the space station "Mir" and the lidar optical axis at the orbit: the station (1), orbit trajectory (2), lidar optical axis (3), ICS center (Earth) (O_i), Earth radius-vector (R_E), ICS2 orientation mode (a), OCSc orientation mode (b).

ORIENTATION OF "MIR" SPACE STATION AND LIDAR OPTICAL AXIS IN LIDAR SENSING SESSIONS

When analyzing the lidar space experiments, we used telemetric information obtained from angle sensors of the Mission Control Center (MCC) about the angles at which the space station-fixed coordinate system was oriented with respect to two basic coordinate systems (inertial and orbital). We also used in our analysis calculated data on the orientation of the lidar axis in the orbital coordinate system. Some information about the basic coordinate

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systems of the "Mir" space station can be found in Refs. 2, 3, and 5.

In Fig. 2. one can see relative positions of the basic orbital coordinate system, $O_0X_0Y_0Z_0$, and space station-fixed coordinate system, $O_SX_SY_SZ_S$, as well as the nadir direction, and azimuth angle ψ and pitch angle ν of the lidar optical axis. Both coordinate systems have same origin at the center of mass of the orbiting complex which is inside its base block. In the general case the axes of the two coordinate systems make up Euler angles.[7] In the OCS mode of the space station orientation the values of these angles should practically be constant, and in the ICS2 mode they continuously change during a flight. As this takes place, the axis "$+O_0Y_0$" is always directed along the radius vector of the station that is opposite to nadir direction. The axis "O_0X_0" is practically directed along the station velocity vector. One also can see in Fig. 2 the longitudinal section of the "Spektr" module by the third quarter of the $X_SO_SY_S$ plane that involves the origin of the lidar optical axis O_l. The point O_l' is the projection of the point O_l onto the plane $X_0O_0Z_0$ (the plane of local horizon).

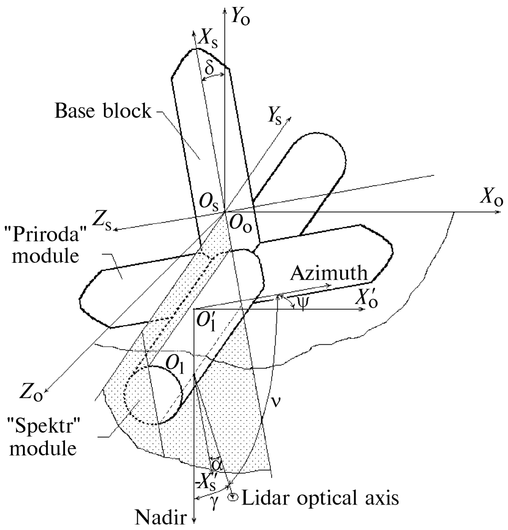

FIG. 2. Mutual orientation of the coordinate axes and the lidar optical axis.

The initial (measured at the ground) orientation of the lidar optical axis about the space station-fixed coordinate system is known because it is determined by design calculations. The optical axis is parallel to the plane $X_SO_SZ_S$ of the space station-fixed coordinate system and makes up an angle $\alpha \approx 1.5°$ counter-clockwise to the axis "$-X_SO_S$", when looking from the "$-O_SY_S$" direction (see Fig. 2.). Based on the initial lidar optical axis orientation, ballistic calculations were made in the MCC of the current values of the azimuth angle $\psi(t)$ (the angle between the velocity vector and the projection of the lidar optical axis onto the plane $X_0O_0Z_0$) and pitch angle $\nu(t)$ (the angle between the plane $X_0O_0Z_0$ and the lidar optical axis), and of the range $D_c(t)$ to the ocean surface for each session of the laser sensing. The pitch angle ν of the lidar optical axis relates to the angle γ of its deviation from nadir by the following formula $\nu = 90° - \gamma$.

Variations of the calculated values of the azimuth $\psi(t)$ and pitch $\nu(t)$ angles for seven laser sensing sessions carried out in fall of 1995 in the orientation mode of ICS2 are presented in Fig. 3.

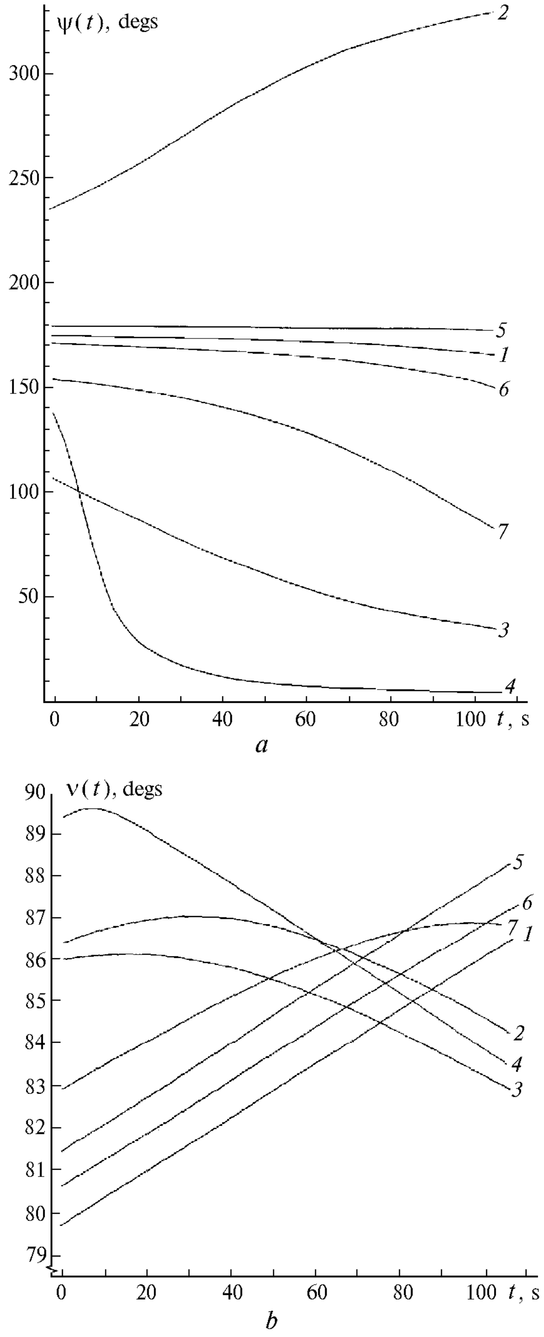

FIG. 3. Variations in the azimuth $\psi(t)$ and pitch angle $\nu(t)$ of the lidar optical axis during the measurement sessions of 1995: on September 8 (1); on September 9 (2); on September 12 (3); on September 15 (4); on September 18 (5); on September 21 (6); and on September 24 (7).

Abscissa in this figure shows current time in a measurement session. In order to make a comparison between lidar data obtained during different sessions, the zeroth moment in time is taken for the first shot in a session while the 20th shot is at 105th second of the session period. Curves *2*, *3*, *4*, and *7* were obtained for moments in time when the lidar optical axis was in the near proximity of the nadir direction. In that case the function $\nu(t)$ reaches its extremum. Other curves (*1*, *5*, and *6*) correspond to the moments when the lidar optical axis only approaches nadir being far from it. It is worth noting that the rate of the azimuth angle variation, $d\psi/dt$, depends on the time derivative $d\nu/dt$ and reaches its maximum when $\nu(t)$ approaches its extremum (curves *2*, *3*, *4*, and *7* in Fig. 3*a*).

During laser sensing session the direction of the lidar optical axis underwent complicated changes relative to the nadir direction even in the absence of random fluctuations of the space station "Mir" orientation. It is seen from Fig. 3*a* that near the orbit plane which corresponds to the azimuth angle of 0 or 180°, the lidar optical axis was in the laser sensing session only on September 18, 1995 (curve *5*) and in the end of the session on September 15, 1995 (curve *4*) after passing of the extremum point on pitch angle.

Calculated orientation of the lidar optical axis was set in the OCSc orientation mode to be at a constant pitch angle $\nu = 90°$ ($\gamma = 0°$). Below we present detailed analysis of the angles at which space station-fixed coordinate system $O_sX_sY_sZ_s$ is oriented with respect to the basic orbital coordinate system $O_oX_oY_oZ_o$ based on telemetric information from gyroscopic sensors of the space station traffic control system.

MEASUREMENT RESULTS ON THE SLANT RANGE OBTAINED IN THE INERTIAL MODE OF THE SPACE STATION ORIENTATION

Earlier[2–4] we have presented some data on measured, $D_m(t)$, and calculated, $D_c(t)$, values of the slant range obtained in 1995 during laser sensing session carried out in the ICS2 flight mode. Figure 4 presents calculated curves $D_c(t)$ (solid lines) and measured values $D_m(t)$ (horizontal bars) for some of these sessions. Numbers at the curves correspond to those in Fig. 3 and show the dates of the experiments. Presentation of the experimental data, $D_m(t)$, as one-second long bars reflects the uncertainty in the measurement time since telemetric data acquired from the space station were decoded with ±0.5 s uncertainty in time.[2–4] No experimental data, $D_m(t)$, in some curves were available because of very low return signals due to cloudiness.

Comparing the data presented in Figs. 3*b* and 4, one can see that there is a time lag between the moments $t_{\max\,\nu}$ and $t_{\min D}$ when the functions $\nu(t)$ and $D_c(t)$ reach their maximum and minimum, respectively. This time lag is 5 to 20 seconds as long. This happens because not always the value of slant range $D_c(t)$ takes its minimum at a maximum value of the pitch angle $\nu(t)$ of the lidar optical axis. The latter may be explained by the fact that the function $D_c(t)$, in addition, depends on the sign of the derivative of the orbit height with respect to time. In the laser sensing sessions carried out the difference $\Delta t = t_{\max\,\nu} - t_{\min D}$ was positive. Table I presents the values Δt for curves depicted in Fig. 3 and 4 determined from the ballistic data.

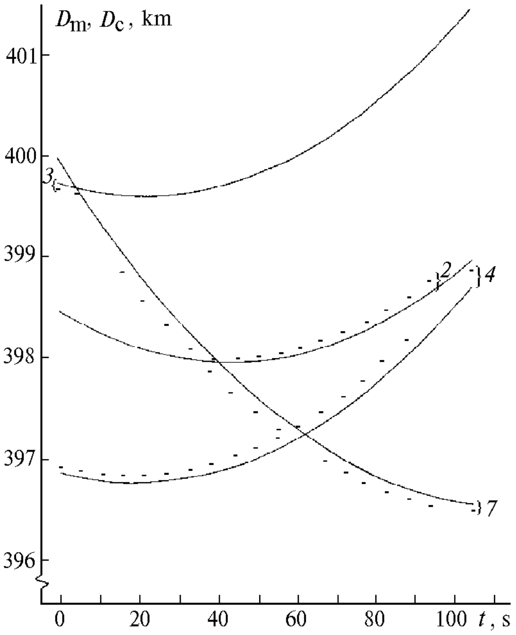

FIG. 4. Measured and calculated slant ranges acquired during the sensing sessions of 1995.

TABLE I.

Curve number	*3*	*2*	*4*	*7*
Δt, s	5	11	11	6

Figure 5*a* shows two characteristic dependences obtained in 1996 when sensing the ocean surface in the south Atlantic (curve *1*) and in the south part of Indian ocean (curve *2*) in the ICS2 orientation mode. In these measurement sessions, according to ballistic calculations, the lidar optical axis was close to nadir direction at the very beginning of the sessions (see Fig. 5*b*). The time difference Δt between maximum in $\nu(t)$ and minimum in $D_c(t)$ reaches 30 s. It is characteristic of these measurements that the range difference $\Delta D = D_c(t) - D_m(t)$ was up to 300 to 400 m while in the sessions of 1995 it did not exceed 150 to 200 m and changed its sign from session to session (see Fig. 4). Possible causes of discrepancy between $D_c(t)$ and $D_m(t)$ values are discussed below.

It was also characteristic of sessions conducted in 1995 and 1996 that no return signals were recorded from the ocean surface when the angle between lidar optical axis and nadir exceeded 10°. In this case the duration of the return signals increased while their amplitude dropped below the first sensitivity threshold of the range finder channel of the lidar.[6]

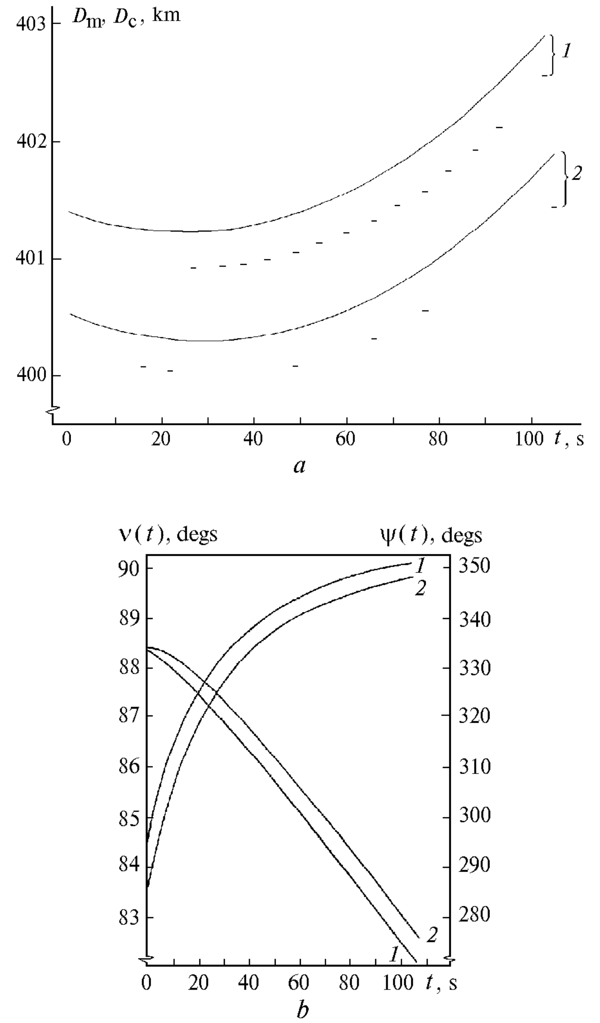

FIG. 5. Results of rangefinding of the ocean surface in 1996 obtained in the ICS2 orientation mode: 02.14.96 (1); 02.15.96 (2); variations in the slant range (a); variations in the azimuth $\psi(t)$ *and pitch angle* $\nu(t)$ *of the lidar optical axis (b).*

MEASUREMENT RESULTS ON THE SLANT RANGE AND POSITION OF THE LIDAR OPTICAL AXIS OBTAINED IN THE ORBITAL ORIENTATION MODE

As was mentioned above the flight mode when the space station-fixed coordinate system is referred to the basic orbital coordinate system $O_0X_0Y_0Z_0$ the optical axis of the lidar is almost permanently looking at nadir during the sensing session. Figure 6 shows some results of lidar sensing of the ocean surface and, incidentally, of cloud fields obtained on dark side of the Earth over the south part of the Pacific ocean. Below the abscissa axis are shown the geographical coordinates of the starting and end footprints of the trajectory and the decree Moscow time (DMT) of the session beginning and termination. It is seen from these figures that the range difference $\Delta D = D_c(t) - D_m(t)$ varies from session to session both in magnitude and sign.

Telemetric information from the station involves data from angular sensors on the Euler angles for the axes of the space station-fixed coordinate system with respect to the ICS and OCS basic coordinate systems, as well as on the angles between corresponding axes of individual systems. Based on data acquired in 1996 we have analyzed random fluctuations of the position of the space station-fixed coordinate system and, correspondingly, the optical axis of the lidar with respect to the basic orbital system of coordinates during the period of each measurement session. For an individual session of 326 s (60 sounding laser shots) there were available from 13 to 23 readings of the angular sensors with the intervals from 6 to 25 seconds between them.

When making analysis of data obtained in the OCSc orientation mode, it is most interesting to consider the values of the angle δ between axes "$+O_0Y_0$" and "$+X_sO_s$" (see Fig. 2). This angle most completely characterizes the position of the lidar optical axis because it is deviated from the "$-X_sO_s$" axis by small angle $\alpha = 1.5°$ and "$+O_0Y_0$" axis direction is opposite to nadir. The value $\alpha = 1.5°$ made it possible to orient the optical axis of the lidar along nadir direction when other angles between axes of $O_0X_0Y_0Z_0$ and $O_sX_sY_sZ_s$ coordinate systems were kept properly. The fluctuations of the "$+X_sO_s$" axis of the space station-fixed coordinate system relative to the basic orbital system of coordinate most completely characterizes fluctuations of the lidar axis relative to nadir direction during a measurement session.

Table II gives the session mean values of the angle $\overline{\delta}$, mean deviations $\overline{\Delta\delta}$ of each reading from $\overline{\delta}$ during the session, and also the maximum value $\Delta\delta_{\max}$ between the successive shots during a session.

As seen from Table II, according to angle sensor's data, only in two last sessions the optical axis of the lidar was within ≈ ±3 min. of arc near the nadir direction. In the other four sessions a systematic variation of the optical axis from nadir was just less than 0.4°. Mean variations of the lidar optical axis position during the session were no more than 2 to 3 min. of arc. Maximum variations of the lidar optical axis between neighbor readings in the interval 6 to 15 s did not exceed 3.3 min. of arc (excluding session on March 5, 1996). The roll or knock in the space station position of $\Delta\delta_{\max} = 0.291°$ that happened on March 5, 1996 was recorded by the angular sensors at 15:43:44 of the decree Moscow time and the value of δ at that moment was 1.440°. In the preceding (7 s before this time) and succeeding (14 s after) samples it was 1.149°. The roll was dominantly on pitch angle, i.e., in the orbit trajectory plane, with a small turn (decrease of the $Y_sO_sY_0$ angle was 0.017°). This roll was also recorded with the lidar in a range measurement 2 s later, at 15:43:46, when the value $\Delta D = D_c(t) - D_m(t)$ decreased by 20 m as compared to the mean value of ΔD at the adjacent measurement points. The calculated value of the increase in D_m due to 0.291° increase in angle δ is 17 m at the average orbit height of 410.8 km. This shows a good agreement between lidar measurements and telemetric information from angular sensors, especially if one takes into account the 2-second time lag between the measurements in two different systems.

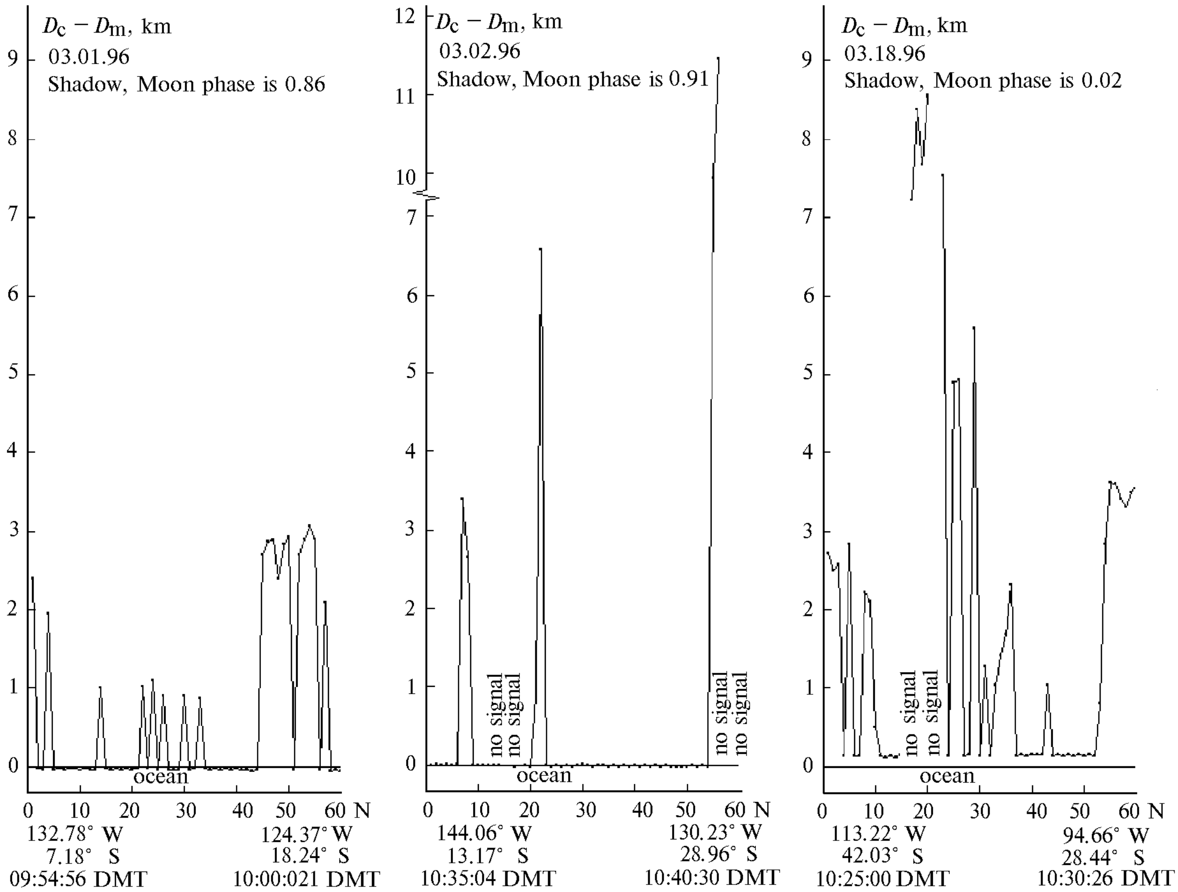

FIG. 6. Some results of lidar sensing of the ocean surface in the Pacific ocean obtained in the OCS orientation mode.

TABLE II.

Data	03.01.96	03.02.96	03.05.96	03.18.96	03.30.96	03.31.96
$\overline{\delta}$, deg.	1.126	1.118	1.132	1.093	1.544	1.548
$\overline{\Delta\delta}$, deg	0.036	0.031	0.039	0.032	0.007	0.009
$\Delta\delta_{\max}$, deg.	0.048	0.055	0.291	0.040	0.043	0.038

SPATIOTEMPORAL UNCERTAINTIES IN THE MEASUREMENT RESULTS

The comparison made between the measured values of the range to the ocean surface, $D_m(t)$, and the calculated ballistic range, $D_c(t)$, show that there exists an alternating-sign systematic difference between those in both modes of the station orientation. Among possible causes of such difference between the measured and calculated data of the slant range there may be the following: 1) inaccurate knowledge of the lidar optical axis position in the space station-fixed coordinate system; 2) errors in the common timing system and, as a result, inaccurate timing of the laser sensing events; 3) uncertainties in calculations by the ballistic codes.

The first cause is a result of summing of all kinds of mechanical uncertainties at the place of the lidar mounting to the window of "Spektr" module, as well as in the fitting assemblies connecting modules of the space station base block. Finally the internal pressure inside the space station may also cause some deformation that will contribute to that mechanical uncertainty. In the final result the error in the lidar optical axis position in the space station-fixed coordinate system is within a cone whose axis makes an angle α = 1.5° with coordinate axis "$-X_sO_s$". The plane angle at the cone vertex is $\Delta\alpha \approx 0.3°$ (see Fig. 2). Analysis of the telemetric information acquired from angular sensors of the space station showed that during a ten-minute flight of the station in the OCSc mode there occur fluctuations in the directions of the space station-fixed coordinate system with respect to the basic orbital coordinate system within ± 0.04° limits. This type of uncertainty leads only to an inessential error (about ± 0.5 m) in determination of the flight height when sounding exactly along nadir direction, while causing an essential shift of the laser footprint on the Earth's surface (up to ± 300 m). In our earlier papers[2,3] we have shown that the value ΔD essentially increases with increasing γ angle, at the error $\Delta\alpha$ being constant. This is especially true for $\gamma > 3°$. As a result of the $\Delta\alpha$ uncertainty, the actual geographical coordinates of the laser footprint on the Earth surface will be shifted with respect to calculated ones.

Uncertainties in timing of the laser sensing events also contribute to the uncertainty in coordinates of an individual measurement. The timing of measurements onboard the space station is performed using the time scale of the common timing system (the decree Moscow time). The time scale used on the space station when writing telemetric control signals on tape recorders uses one-second intervals. As a consequence the minimum error in the measurement timing, D_{m}, is ± 0.5 s since the period between laser shots is 5.53 s. This error immediately gives rise to a ± 3.85 km uncertainty in the trajectory footprint. The maximum uncertainty can reach 1 s because of summing up the time lags in the relay circuits transferring the telemetric signals from the lidar blocks.

An additional discrepancy between D_{c} and D_{m} may appear due to the errors in the radar control of the space station orbit trajectory, because these data are the input parameters for calculation of the station orbit. In the north hemisphere the error in the calculated orbit height, $H_{\mathrm{c}}(t)$, may reach 150 m and in the south hemisphere the error increases since there are no radars here to control the station orbit. Since all ballistic calculations refer to the moment T_{e} in time and to longitude L_{e} of the footprint where the trajectory projection crosses the equator, the time uncertainty of 1 s additionally gives rise to the error in $H_{\mathrm{c}}(t)$ of 10 to 20 m (because of ellipticity of the orbit) and to a shift in the footprint coordinates up to 7.7 km.

CONCLUSION

The experiments carried out with a spaceborne lidar "Balkan" have demonstrated quite good capability of this device to accurately measure the orbit height of the space station "Mir". We have made analysis of the time stability of the lidar optical axis orientation during the measurement sessions. Analysis made enables us to reveal some possible causes of the systematic discrepancies between the calculated ballistic data and measured values of the slant range obtained in two modes of the space station orientation.

The data on possible shifts of the space station-fixed coordinate system axes during a flight should be taken into account when processing the Doppler lidar information.[8] We hope that the experience of the spaceborne lidar experiments achieved will provide a better basis for future investigations.

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REFERENCES

1. J.L. Bufton, Proc. IEEE **77**, No. 3, 463-477 (1989).
2. Yu.S. Balin, A.A. Tikhomirov, and S.V. Samoilova, Atmos. Oceanic Opt. **10**, No. 3, 209–220 (1997).
3. Yu.S. Balin, S.V. Samoilova, and A.A. Tikhomirov, Proc. SPIE **2956**, 8–18 (1996).
4. Yu.S. Balin, A.A. Tikhomirov, and S.V. Samoilova, Kosm. Nauka Tekhnol. **4**, Nos.1–2, 1–7 (1998).
5. Yu.S. Balin and A.A. Tikhomirov, Kosm. Nauka Tekhnol. **3**, Nos. 1–2, 26–33 (1997).
6. Yu.S. Balin, I.V. Znamenslii, V.E. Zuev, et al., Atmos. Oceanic Opt. **8**, No. 9, 711–717 (1995).
7. G. Corn and T. Corn, *Handbook on Mathematics for Scientists and Engineers* (Nauka, Moscow, 1968), 720 pp.
8. Ch. Werner, B. Brand, and E.F. Jochim, Proc. SPIE **2581**, 148–162 (1995).