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SPACE GEODESY AND GEODYNAMICS

Estimation of the Accuracy of Geostationary Satellite Observations

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Abstract—Continuous monitoring of artificial space objects requires periodic quality control of observational data. Estimating the internal accuracy of observations in the form of an RMS error of positions makes it possible to monitor and detect outliers in primary data array. For artificial satellites of the Earth, the orbital elements calculated at the Research Institute Nikolaev Astronomical Observatory (RI NAO) can be externally compared with the data of the International Laser Ranging Service (ILRS) or the Global Navigation Satellite System (GNSS). Such a comparison makes it possible to detect time synchronization problems and to identify and evaluate systematic errors. At the RI NAO, regular observations of artificial satellites in different orbits using several telescopes have been carried out for more than 10 years, and a catalog of orbital elements in the two-line element (TLE) format is maintained. The software for calculating orbital elements has been developed in cooperation with the Astronomical Observatory of the Odessa National University. This article presents the analysis of the processing results of an array of observations from 149 geostationary satellites (GSS's). The observations have been made during 2020...2021 using the RI NAO telescope complex. Time synchronization has been provided by the Resolution-T GPS receiver with an RMS error of 40 ns. All GSS observations have been carried out using the combined observation method developed at the RI NAO. A total of 134 461 GSS positions have been obtained for which the residual $O-C$ differences with respect to the orbit calculated at the RI NAO have been determined. The RMS error of the GSS positions in the apparent magnitude range $9^m...13^m$ is 0.5" in right ascension and declination. A comparison of the GSS orbital positions calculated from the RI NAO orbital elements and the ILRS website data shows that the differences between the corresponding geocentric Cartesian coordinates at the start of the prediction are $dX = 0.72$ km, $dY = -0.52$ km, and $dZ = 1.28$ km.

Keywords: ground-based CCD observations, geostationary satellites, orbital elements

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INTRODUCTION

Since the beginning of the space age, the number of man-made objects in the near-Earth space has been increasing due to new spacecraft launches. The space debris that accumulates in orbit poses a serious threat to both the safety of space missions and the Earth's population. As of early October 2021, according to the Celestrack website, the total number of catalogued space objects was 49 324, of which only 4931 are operational [https://celestrak.com/satcat/boxscore]. Since the geostationary orbit is the most favorable for solving many scientific, military, navigational, and other tasks, most of the operating spacecraft are located in this orbit. With the increasing use of satellites by developed countries, it is becoming clear that the geostationary orbit is not limitless and, thus, significant effort should be expended to maintain space control systems. Although the coordinates of geostationary satellites (GSS's) are determined more accurately by radiopositioning, optical observations remain the main source of information for monitoring and cataloging objects in this industry. In 2011, a Ukrainian network of optical stations for near-Earth space research network [http://mao.uran.ua/umos/index.php?slab=slabid-7]) was created for regular optical observations of space objects. The Research Institute Nikolaev Astronomical Observatory (RI NAO) is an active participant of this network in the field of positional observations (the statistics of observations for the last 3 years is given in Table 1). The purpose of this work is to obtain estimates of the positional accuracy of

Table 1. Statistics of GSS positions obtained at the RI NAO

Year	Number of nights	Number of objects	Number of positions
2019	72	30	14266
2020	150	149	57271
2021*	102	61	77190
Total	324	149	148727

* As of Oct. 1, 2021.

the optical observations of artificial satellites based on the results of processing the array of GSS observations for 2020...2021 and to obtain estimates of the external accuracy of these observations by comparing them with the data of the International Laser Ranging Service (ILRS) [https://cddis.nasa.gov/archive/slr/].

METHOD OF OBSERVATION

For positional observations of objects with large apparent velocities, the RI NAO developed and put into practice a set of original methods, the common feature of which is that the telescope is immobile during frame formation (i.e., there is no mechanical tracking) [4, 6]. The GSS observations are carried out using the combined method [3], the essence of which consists in separating the processes of obtaining images of the program object and the reference stars on different frames on a stationary telescope. Different methods of signal accumulation are used to obtain point images of the object and stars, which makes it possible to vary the exposure time depending on the apparent velocity and brightness of the object. Figure 1 shows an example of the images obtained from observations of the *IRNSS-1F* (41384) satellite on the night of May 4, 2021, on the KT-50 telescope of the Mobitel complex.

TELESCOPES

Optical GSS observations are carried out on three telescopes that have been upgraded or created at the RI NAO [1, 7]. All telescopes are equipped with full-frame CCD cameras. Observations are synchronized on signals of the GPS-receiver Trimble Resolution-T [https://xdevs.com/doc/Trimble/Data%20Sheets/Resolution%20T.pdf]. The observation process on all telescopes is controlled by a distributed software package and can be carried out in remote mode. The information about parameters of telescopes is given in Table 2.

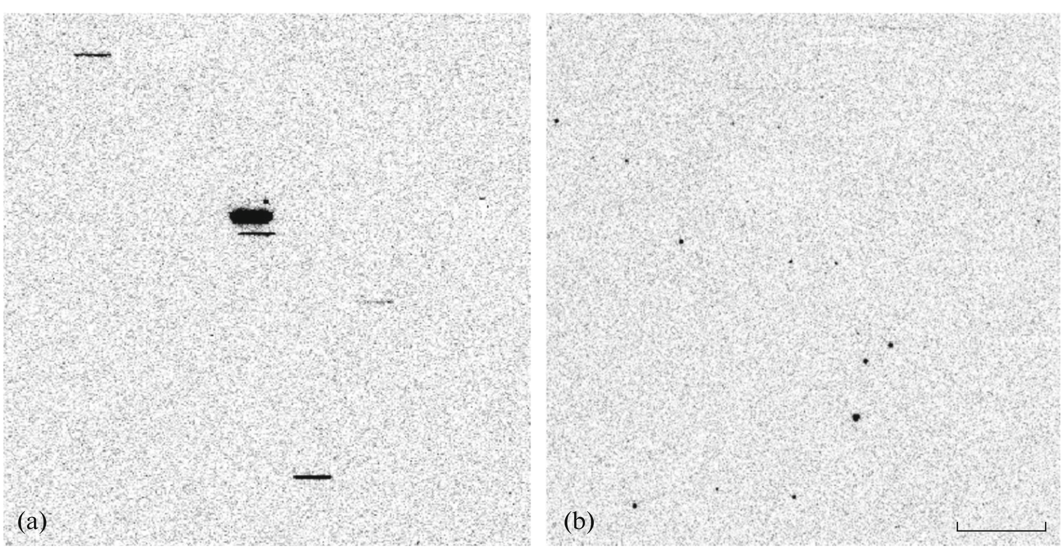

Fig. 1. Fragments of the frames from the observations of the *IRNSS-1F* (N41384) satellite on the night of May 4, 2021, on the KT-50 telescope: (a) satellite and (b) reference stars.

Table 2. Basic characteristics of the instruments used for the GSS observations

Telescope	Fast Robotic Telescope	Mobitel complexes	
		KT-50	Mezon
D/f, mm	300/1510	500/3000	230/800
CCD camera: size, pel	Apogee Alta U9000 3056 × 3056	Apogee Alta U9000 3056 × 3056	Apogee Alta U9000 3056 × 3056
Pixel size, μm	12	12	12
Scale, "/pel	1.66	0.84	3.21
Field of view, '	84 × 84	43 × 43	156 × 156

PROCESSING

The first stage includes filtering of the obtained images and measurement of rectangular coordinates of the object in the matrix system. In order to obtain the topocentric equatorial coordinates, a modified method of astrometric reduction (MAR), which is a modified scheme of the classical Turner method for photographic reduction of observations [2], is used. The main idea of the MAR is the interpolation of the reduction coefficients obtained from the processing of the frames with the reference stars to the time that corresponds to the frame with the object [5].

PROCESSING OF RESULTS AND INTERNAL ACCURACY

The data set obtained from the processing of the observations contains the topocentric equatorial coordinates (right ascension α and declination δ) and the apparent magnitudes m of the satellites at the time of the observation in the reference catalog system. The histogram of the distribution of the observed objects according to the values of apparent magnitudes m is shown in Fig. 2.

The histogram shows that GSS's are quite bright objects (95% of them have apparent magnitudes between 10^m and 13^m). As a result, they can be observed in a shortened exposure mode, which makes it possible to obtain 25...35 positions for each of 20...25 objects during one night of observations.

Orbital elements in the TLE format, which correspond to the Simplified General Perturbations (SGP4/SDP4) motion model, and GSS ephemerides in Consolidated Prediction Format (CPF) are calculated using the software developed together with the Research Institute Astronomical Observatory of Odessa National University [8]. Orbital elements are calculated on the basis of several observational series, which minimizes the error in their estimates. The RMS error of residual differences ($O-C$) of the satellite's topocentric equatorial coordinates, where O is the observed positions and C is the positions calculated from the orbital elements, can be used as an estimate of internal accuracy. The RMS error of the

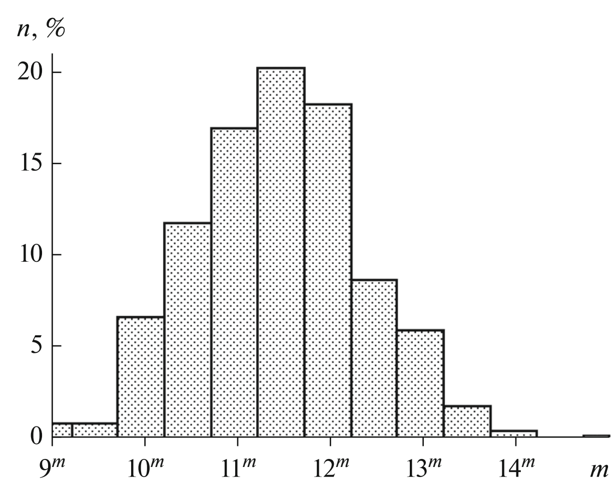

Fig. 2. Histogram of the GSS distribution with respect to the apparent magnitudes.

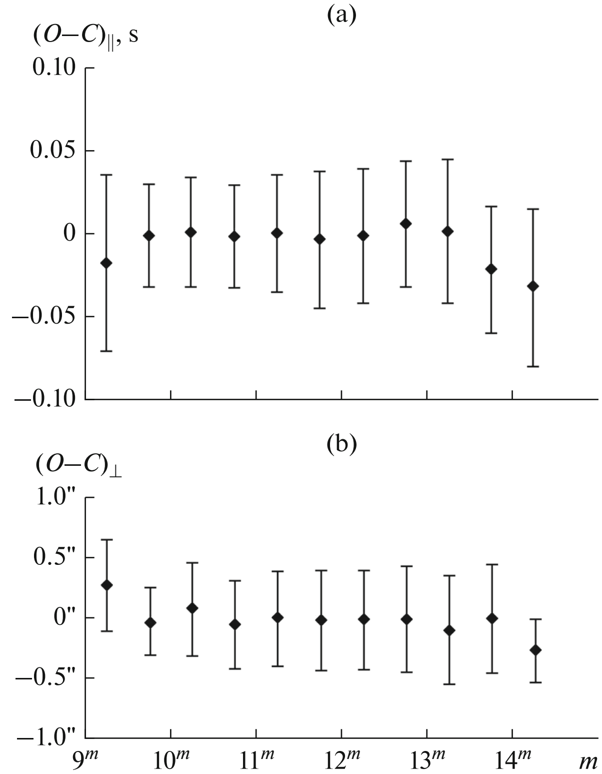

Fig. 3. Dependence of the residual differences *O–C* on the apparent magnitude *m* of the object: (a) along the satellite's orbit and (b) perpendicular to the satellite's orbit.

GSS positions in the apparent magnitude range $9^m...13^m$ is 0.5" for both right ascension and declination. The residual differences (*O–C*) along and perpendicular to the satellite's orbital motion were also calculated. The dependence of (*O–C*) on the apparent magnitude of the object is shown in Fig. 3. In this case, the mean values of the RMS error of the residual differences (*O–C*) are 0.5" (0.035 s) and 0.5" for the directions along and perpendicular to the satellite's orbit, respectively.

ESTIMATION OF EXTERNAL ACCURACY

In order to estimate the external accuracy of our observations, we used high-precision observational data from the ILRS satellites from the NORAD catalog [https://cddis.nasa.gov/archive/slr/cpf_predicts/]. Two approaches to the external comparison were implemented. In the first case, we compared the values of the state vectors calculated from the orbital elements in the TLE format, which served as initial prediction conditions. The object state vector includes the components of geocentric Cartesian coordinates and velocity components in the International Celestial Reference System (ICRS) for the J2000 epoch. The necessity of predicting is caused by the fact that the compared orbital elements in the TLE format have different epochs. A simplified SGP4/SDP4 motion model, namely its implementation in the Python 3 programming language, as well as the standard library *astropy* [https://docs.astropy.org/en/stable/index.html] were used to convert the TLE into the state vector format and make predictions.

Figure 4 shows the results of comparison of the predicted coordinates of the object *IRNSS-1F* (N41384) with high-precision geocentric coordinates calculated by the ILRS service in the CPF format in the International Terrestrial Reference System (ITRS) as dependences of differences on time. Figure 4a shows the differences calculated for the initial conditions obtained from the NORAD catalog in the TLE format for the epoch JD = 2459009.73472503. The Julian date JD = 2459009.5 (June 8, 2020, 12:00 UTC) was chosen as the starting point for the t0 prediction. The prediction period was 7 days (168 h). Figure 4b represents the same differences for the epoch JD = 2459008.41875000, but the predicted initial conditions were calculated using the RI NAO model in this case. The comparison showed that the values of differences with the positions obtained by the ILRS were $dX = -5.95$ km, $dY = 7.4$ km, and $dZ = 0.52$ km at the beginning of the prediction for the initial conditions from the NORAD catalog and they were $dX = 0.72$ km,

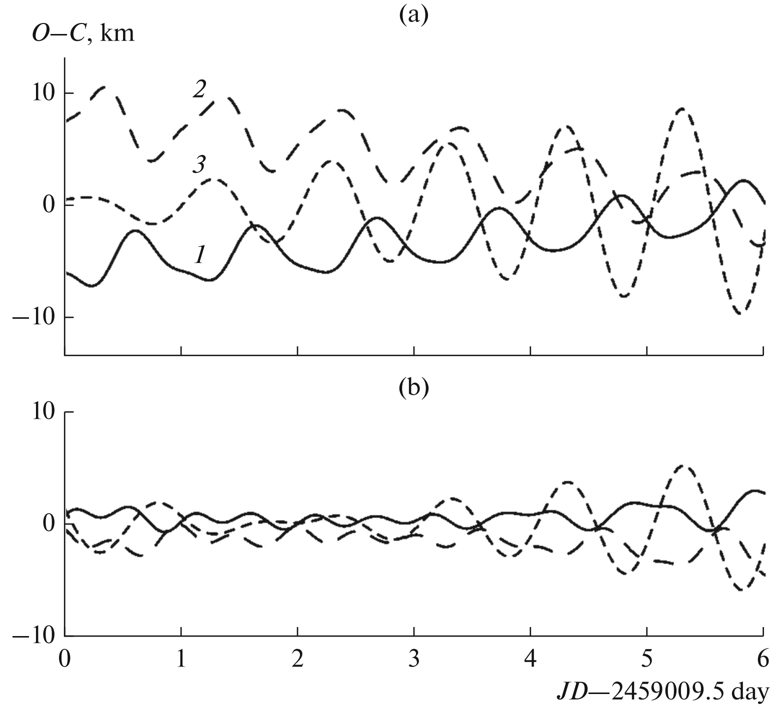

Fig. 4. Dependence of the residual differences *O–C* on time (a) according to the NORAD catalog and (b) according to the RI NAO data. Curve *1* indicates *dX*, *2*, *dY*, and *3*, *dZ*.

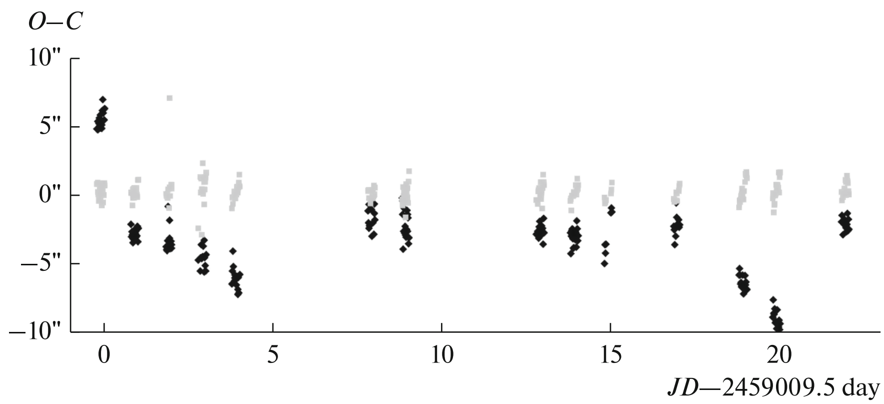

Fig. 5. Residual differences *O–C* in comparison with the ILRS data for the object *IRNSS-1F* (N41384). Gray dots show declination and black dots show right ascension.

$dY = -0.52$ km, and $dZ = 1.28$ km for the initial conditions calculated at the RI NAO. As can be seen from the figure, even despite the shortcomings of the simplified motion model, the change in the residual differences with time for the 7-day prediction period also confirms that more accurate GSS orbital elements can be obtained.

The second approach consists in a direct comparison of the GSS topocentric equatorial coordinates obtained from the observations with the equatorial coordinates calculated from the interpolated values of high-precision geocentric positions in the CPF format from the ILRS website. The interpolation was performed by the Lagrange polynomial over 10 points. The coordinate systems were transformed in the Python 3 programming language using the standard library *astropy*. Figure 5 shows the calculated differences for the object *IRNSS-1F* (N41384) over the observation period from June 8, 2020, to July 17, 2020 (39.24 days). As can be seen, the standard deviation of the residual differences for declination is 1" and that for right ascension is 2". It should be noted that the differences in declination have almost no systematic bias, in contrast to the differences in right ascension, for which the systematic bias is 2.5". Significant outliers are observed on some observation dates. They may have been caused by synchronization errors during the observations.

CONCLUSIONS

During 2020...2021, 134 461 positions for 149 GSS's were obtained from optical CCD observations at the RI NAO. The RMS error of the observations is close to 0.5" for both coordinates for objects with apparent magnitudes within $9^m \ldots 13^m$.

The comparison with the ILRS data showed that the calculation accuracy of the orbital elements using the RI NAO software is higher than the accuracy of the corresponding data in the NORAD catalog. The differences between the corresponding geocentric rectangular positions are 0.72, –0.52, and 1.28 km, respectively, for the coordinates X, Y, Z for the epoch 2459009.5 (July 8, 2020, 12:00 UTC), which corresponds to the prediction start time. Prediction of the initial conditions in the state vector format for a 7-day period also showed the advantage of the orbital elements calculated using the RI NAO software. The external comparison of the measured equatorial GSS coordinates with the high-precision ILRS data revealed the presence of irregular outliers in the right ascension system, which can be due to synchronization errors in the observation process.

CONFLICT OF INTERESTS

The authors declare that they have no conflicts of interest.

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