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NAO Catalog of Geocentric State Vectors of Geosynchronous Space Objects

I. V. Kara[a], Y. S. Kozyryev[b], Y. S. Sybiryakova[b], and O. V. Shulga[b]
[a]*Odessa Astronomical Observatory, ul. Marazlievskaya 1v, Odessa, 65014 Ukraine*
[b]*Nikolaev Astronomical Observatory, ul. Observatornaya 1, Nikolaev, 54030 Ukraine*
e-mail: lionkiv@gmail.com, evg_sibir@mail.ru

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Abstract—Results of observations of geosynchronous space objects for the period of 2008–2010 are presented. The estimation of observation data errors is given. The process of calculating the state vectors is briefly described. The results of comparison of the Nikolaev Astronomical Observatory catalog with the NORAD orbit catalog are presented.

Keywords: geosynchronous space objects, state vector, catalog, ephemerides
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1. INTRODUCTION

Based on the data of the catalog of the European Space Agency *Classification of Geosynchronous Objects* (Choc, Jehn, 2010), 1238 space objects (SO), 68% of them being space debris, had been detected in geosynchronous orbits by January 2010. With the number of debris objects in the geostationary region increasing, their intercollisions, which can yield an avalanche-like increase in the amount of hard-to-detect small-size debris, become inevitable. Such a development will make it impossible to use geosynchronous orbits due to a high risk of a collision of an Earth artificial satellite with debris objects. Owing to the uniqueness and importance of the geostationary region, it is necessary to perform nonstop tracking of the cataloged debris objects and searching for those that are not listed in the catalog. For this problem to be solved, it is necessary to develop a continuously updated catalog of geocentric state vectors of debris objects. Based on this catalog, it is possible to perform regular online evaluation of the risk of collisions of operating satellits with debris.

The catalog of geocentric state vectors presented in the present paper has been formed based on the observation data obtained at the Nikolaev Astronomical Observatory (NAO) in 2008–2010 with the Fast robotic telescope FRT ($D = 300$ mm, $F = 1500$ mm) using a combined method of CCD-observations (Kozyryev et al., 2008). The parameters of orbits of the observed objects and ephemerides were calculated using mathematical software (MSW) developed by the specialists of the Odessa and Nikolaev Astronomical Observatories.

2. CALCULATION OF REFERENCE STATE VECTOR AND ELEMENTS OF SO ORBITS

In the present paper, the state vectors and ephemerides of SO are calculated using a numerical model of motion developed at the Odessa Astronomical Observatory. The SO state vector includes components of geocentric Cartesian coordinates and velocity components in the ICRS system at the J2000 epoch. The motion model takes into account the following perturbations:

(1) perturbation from the geopotential (expansion up to the 15th order);

(2) perturbations from the Moon and the Sun (where positions are calculated using the DE/LE 405 numerical model);

(3) perturbation from tides in the solid crust (the Love's model in the form of additional coefficient to the second and the third zonal harmonic of the geopotential); and

(4) perturbation from light pressure.

The differential equations of motion are solved using the Everhart classical numerical method of the 15th order with autocorrelation of the integration step that provides the integration accuracy on the order of 10^{-10} (Bazyey, Kara, 2009).

Observations—namely, topocentric angular coordinates of an SO obtained as a result of optical observations—serve as source data for calculating the state vector. The observations are grouped into series clustering the data obtained at one orbit pass of the SO orbit. The state vector is calculated in two stages: calculation of the primary vector and its specification. The primary vector is calculated based on one reference observation series using the Laplace analytical method (Eskobal, 1970).

The vector is specified based on several observation series, which minimizes the errors in its estimation. The process of specification is iterative one and is accomplished using the method of differential corrections (Eskobal, 1970) until the minimal difference between the SC angular coordinates obtained based on observations and the calculated ones is reached (O–C). The residual (O–C) makes it possible to evaluate the quality of observations and determine if the measurements belong to one SO.

The mathematical model of SO motion is implemented in the MSW intended for observation data processing. The results of MSW processing of the observations are as follows:

(1) the SO state vector, orbit elements;

(2) the residual (O–C) obtained when calculating the state vector; and

(3) the SO ephemerides (targeting), as well as (O–C), between the observations that were not part of the calculations of the state vector and the ephemerid.

The orbit elements calculated from the state vector are used for carrying out a comparison with other catalogs. The residual (O–C) obtained in the process of the state vector determination make it possible to estimate a random observation error and belonging of the measurements to one SO. The (O–C) between the observations that have not participated in the calculation of the state vector and the ephemerid allow evaluating the accuracy in predicting the SO motion. The SO ephemerides are used for carrying out new SO observations aimed at specifying the state vector.

3. RESULTS OF OBSERVATIONS OF GEOSYNCHRONOUS SOs

The coverage and the efficiency of the FRT telescope being taken into account, a list of the observed SOs consisting of 73 geosynchronous SOs with the longitudinal drift velocities less than 20°/day was formed. The hour angle coverage of the FRT telescope was from –30° to +60° from the meridian, and the declination coverage was from –25° to +70°. The efficiency is, on average, 25 SOs per night. The following objects have been selected from the catalog of the European Space Agency *Classification of Geosynchronous Objects* (Choc, Jehn, 2010):

(1) 38 D-class objects (objects in drift orbits);

(2) 33 L1-class objects (objects in liberation orbits around the Eastern stable point (longitude 75° East); and

(3) 2 C2-class objects (objects under longitudinal and inclination control; inclination is smaller than 0.3°).

The observations were carried out at the FRT telescope using precalculated ephemerides. The ephemerides were formed based on the orbit elements from the NORAD catalog. The FRT telescope is equipped with a Maksutov-system objective (D = 300 mm, F = 1500 mm) and a CCD camera Alta U9000 (3056 × 3056 pixels, 12 × 12 μm) mounted on a revolving platform. The telescope field of view is 83.2 × 83.2′, and the scale without binning is 1.63″/pixel. The CCD camera can be operated in two modes—namely, a charge accumulation mode and a time delay integration mode. The observations were carried out with the combined method using a revolving platform. The reference stars were imaged in the accumulation mode of the CCD camera. The geosynchronous SOs were imaged in the time delay integration mode. A modified reduction model was used for reduction of the observation (Kozyryev et al., 2010).

Based on the observations data taken during the period of 2008–2010, a catalog of 31883 positions of 67 geosynchronous objects has been formed. The catalog is represented as a text file containing the name of the observation station, the epoch for which the coordinates were calculated, the object number in the NORAD catalog, the date (day, month, and year), the time (hours, minutes, and seconds accurate within the fourth sign after the point), the right ascension (degrees, minutes, and seconds accurate within the fourth sign after the point), the intrinsic computation accuracy, and the magnitude.

To estimate the error in determining the positions based on the observations listed in the catalog, the (O–C) positions were calculated with respect to the computed orbit. The (O–C) values were grouped by SO magnitude with the step 0.5^m. After that, the mean-square errors (MSEs) were obtained for each group. The RMSs of the SO positions were within the range from ±0.33″ to ±0.66″ for the right ascension and from ±0.26″ to ±0.91″ for the declination (Fig. 1a) that corresponds to the intrinsic accuracy of identification of reference stars with the UCAC2 catalog. As far as the magnitude is concerned, the majority of the SOs obtained based on the observations are within the range of 12.5^m–14^m (Fig. 1b).

Table 1 lists MSEs in determining the positions of geosynchronous SOs for different observation stations. Based on the results of observations at the Shajn reflecting telescope (ZTSH) at the Crimean Astrophysical Observatory, the estimates of the intrinsic accuracy in determining the position given in (Birukov et al., 2008) are better than 0.5″.

Based on the aforementioned data, the accuracy of observations performed with the FRT telescope at NAO corresponds to the best level of accuracy for this kind of observation.

4. CATALOG OF GEOCENTRIC STATE VECTORS OF GEOSYNCHRONOUS SO

Based on the data of the catalog of positions, the state vectors and orbit elements of SO have been calculated. Based on the results of the calculations, a cat-

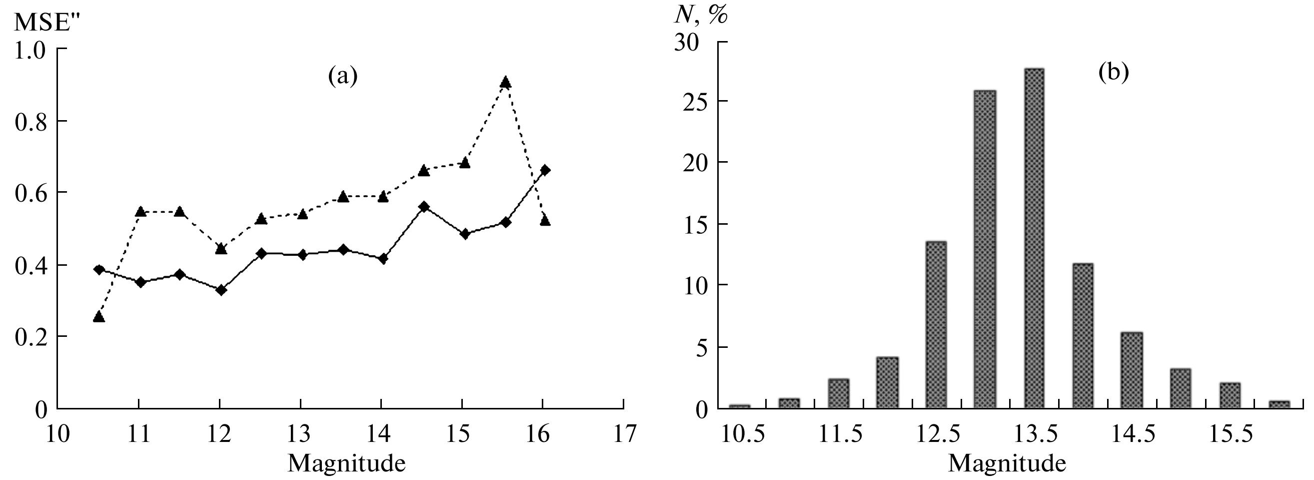

Fig. 1. (a) intrinsic accuracy of the calculation of geosynchronous SO coordinates as a function of magnitude; (b) SO distribution by magnitudes, where N is the number of object positions (%).

alog of geocentric state vectors of geosynchronous SOs has been formed. It includes 179 orbits of 65 geosynchronous SOs. The catalog format is presented in Table 2, where No. is the number in the Norad catalog; *X*, *Y*, and *Z* are the rectangular coordinates of SOs in the geocentric coordinate system at the J2000.0 epoch (in meters); and *Vx*, *Vy*, and *Vz* are the components of the SO velocity (in m/s).

The quality of state vectors can be analyzed by comparing them with the data of other catalogs of orbit parameters and by evaluating the accuracy of the prediction of ephemerides. In the present paper, the forecasting error was determined as the difference between the positions obtained based on the observations and the ephemerides calculated based on the state vector. Such comparison characterizes not only the quality of the calculated state vector, but also the quality of the applied numerical model.

Analysis of the comparison data revealed the dependence of the error in calculating state vectors and, as the result, of ephemerides on the number of the observation orbit pass in calculation of the state vectors. The calculation error was estimated based on the observation of SO 7392. In the first case, the state vector was calculated based on the observation data obtained for one orbit pass; in the second case, for two orbit pass. Based on these state vectors, the ephemerides were calculated in the time period up to four days and the differences between the observations and the ephemerid (O–C) were obtained. In the first case, the (O–C) for the right ascension reached ±100″; that for the declination, ±20″. In the second case, the (O–C) for the right ascension did not exceed ±3″; that for the declination, ±5″. This means that the state vectors calculated based on the observation data for one orbit pass cannot be used in long-term prediction, but, however, in the case of search observation, they can be

Table 1. Mean-square error of observations of geosynchronous SOs

Organization	Telescope	MSE (″)
Terskol branch of INASAN (Andreev et al., 2008)	Zeiss 2000	0.5
Terskol branch of INASAN (Sergeev et al., 2009)	Zeiss 2000	0.3–0.4
Gissar Observatory of Tajikistan (Gulyamov, Minikulov, 2008)	High-accuracy astronomic facility	less than 2
Ural State University (Zakharov et al., 2008)	SBG	1.5–3.5
Ural State University (Zakharov et al., 2008)	AZT 3	less than 1
NAO	FRT	0.26–0.91

Table 2. Format of the catalog of geocentric vector states

No.	MJD	*X*[m]	*Y*[m]	*z*[m]	*Vx*[m/s]	*Vy*[m/s]	*Vz*[m/s]
7392	54924.00096	–20502272.0	–35713381.6	–9265188.3	2670.9	–1516.2	–60.6

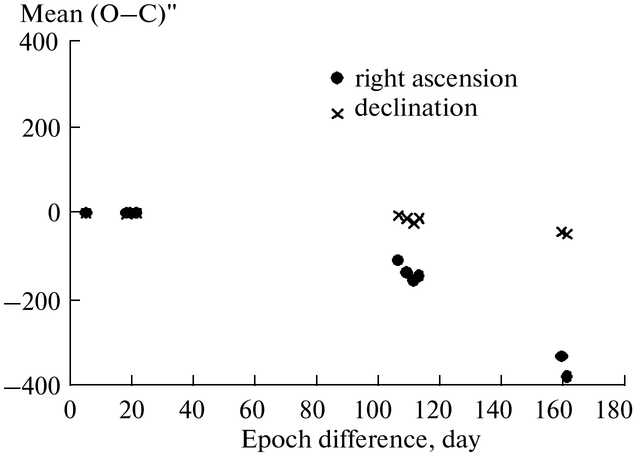

Fig. 2. Dependence of (O–C) on epoch difference for SO 7392.

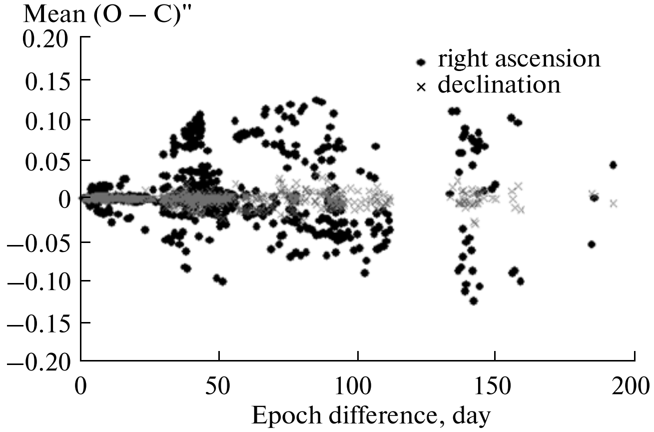

Fig. 3. Module of the mean (O–C) as a function of epoch difference.

applied for determining ephemerides for the period of one to four days. Taking this into account, the state vectors entering the catalog have been calculated using the observations for two or more observation orbit pass.

When comparing the observations with the ephemerid obtained from the state vectors calculated based on the observations for two and three SO orbit pass, the results did not substantially change. Table 3 lists the results of a comparison of observations with the ephemerid for SO 15181. The ephemerides were calculated for time periods up to two years. The table gives the differences of the epochs between the epoch of the observation and the epoch of the state vector based on which the ephemerides have been calculated.

Also paper studied the dependence between the observations and ephemerides on the prediction time period. Figure 2 plots the dependence of the difference between the observation data and the ephemerid on an increase in the forecasting time period for the SO 7392. Each point on the plot corresponds to the mean of (O–C) for a series of observation obtained for one orbit pass of the SO orbit.

It is seen from Fig. 2 that (O–C) increases with an increase in the epoch difference. As far as the right ascension is concerned, the (O–C) value is 7.7 times larger than that for the declination. A large value of the (O–C) for the right ascension is likely to be related to insufficient taking of the perturbing factors into account.

The dependence of the difference between the observations and the ephemerid on the forecasting time period was also analyzed for all state vectors entering the catalog. Figure 3 gives the dependence of the mean (O–C) on the forecasting time period. Each point on the plot corresponds to a series of observations for one orbit pass of the SO orbit that is in agreement with the intrinsic accuracy of identification of the reference stars with the UCAC2 catalog.

It is seen from Fig. 3 that the error of ephemerides calculations based on the right ascension does not exceed ±0.15°; that based on the declination, ±0.05°. The theoretical estimation of the ephemerides error in case of forecasting for 200 days presented in (Misci et al., 2005) is from 0° to 0.35°. The field of view of the FRT telescope being 1.3°, such an error makes it possible to perform observations of the SOs entering the catalog not more often than once in 200 days. The accuracy of the ephemerides calculations, the efficiency of the FRT telescope, and the meteorological conditions in the city of Nikolaev allow specifying the state vectors of 700 SOs once every half a year.

For the time period from 200 days to two years, the error of ephemerides calculations sharply increases (as far as the right ascension is concerned). By the right ascension, the (O–C) for 33% of the orbits does not exceed ±0.2°; that for 67% of the orbits is within the range from ±0.2° to ±1.2°. By the declination, the (O–C) for 75% of the orbits does not exceed ±0.05°; that for 25% of the orbits is within the range from ±0.05° to ±0.13°.

Table 3

Mean difference of epochs (day)	Mean (O–C)			
	two orbit pass		three orbit pass	
	ra″	dec″	ra″	dec″
7	–0.63	–0.02	–0.41	–0.11
39	–8.62	0.88	–6.79	0.68
53	–36.76	–3.03	–34.82	–2.87
749	–454.97	4.99	–1457.9	3.71

CONCLUSIONS

(1) The numerical model of the SO motion and the software for processing the observations that allows calculating the SO state vector, orbit elements, and the ephemerides; estimating the random observation error; and evaluating the forecasting accuracy have been developed.

(2) There have been obtained and listed in a catalog of positions at the J2000 epoch 31 883 positions of 67 geosynchronous SOs in the equatorial system of coordinates. The mean-square error of observations of the SOs of the magnitude 10–16 was from $\pm0.33''$ to $\pm0.66''$ (by right ascension) and from $\pm0.26''$ to $\pm0.91''$ (by declination) that corresponds to the best world level of accuracy for the observations of geosynchronous SOs.

(3) The obtained observations have been used for calculating 179 state vectors of 67 geosynchronous SOs. These data have been used to form the catalog of state vectors of geosynchronous SOs.

(4) Based on the obtained state vectors, the ephemerides for the following observation epochs have been calculated and the error in ephemerides calculations has been estimated. The error of ephemerides calculations for the time period of 200 days does not exceed 0.15° (by right ascension) and 0.05° (by declination), which corresponds to the world level of accuracy of simulation of the motion of geosynchronous SOs.

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