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MONITORING THE ACCURACY OF OBSERVATIONS OF PASSIVE OBJECTS ON THE BASIS OF THE INTERNATIONAL LASER RANGING SERVICE (ILRS) DATA

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ABSTRACT. Today, the problem of pollution of the near-Earth space environment is becoming more acute. In view of that, a larger number of stations for observation and tracking of artificial earth satellites (AES) and space debris objects have been set up. The accuracy of the ephemerides of such objects depends on the quality of the observations obtained. Therefore, the possibility of efficient quality control and monitoring the accuracy of the gathered observations is extremely essential. The suggested method allows of promptly conducting a check on the correctness of the data obtained. The coordinate data of the International Laser Ranging Service (ILRS) are assumed as a basis of the method mentioned above. The developed mathematical software (MS) enables observers to analyze their observations efficiently and without assistance in order to reveal and solve arisen instrumental problems opportunely.

Introduction

At the present stage of development of space science and technology, the mankind has already faced the problem of pollution of the near-Earth space environment. The pollution occurs due to spent rocket stages abandoned in orbit and AES on-orbit explosions generating numerous uncontrolled objects. Such explosions can be caused by collisions between AES or by AES collision with space debris objects. Collisions between AES are still a rare case. That problem of AES explosions has just been worsening year by year. The number of AES launches has been augmenting, and the probability of collisions in space has been increasing simultaneously. That is why more and more observatories allot observation instruments tasked for observation, cataloging and tracking of space debris objects and AES. The creating of catalogues of potentially hazardous objects in the near-Earth space will enable to predict collisions and to preserve expensive satellites, and not to increase the number of perilous objects. When generating such catalogues, it is necessary to regularly monitor the quality of the observations gathered. The accuracy of the obtained ephemerides straightly depends on the quality and correctness of the data. Such monitoring can be conducted either by an observer independently or with assistance of specialists from other observatories. The second alternative lowers manifold the efficiency of detection and solution to an observation accuracy problem if there is any. In this case, the ability of an observer to independently check up the accuracy of observations before their passing to the customer is of great value.

Proceeding from the grand necessity of such monitoring the accuracy of observations, the task to discover a method of observers' independent monitoring the quality of the observations obtained by them was set. The mathematical software (MS), developed on the basis of the discovered method, should enable an observer to promptly conduct a check on the correctness of observations. By using the MS, it will be possible to calibrate either new observation instruments or upgraded available ones in order to increase the accuracy of observations.

Using the ILRS data to monitor the observations obtained

The direct comparison of actual observations with reliably correct reference observations of the same objects is the most reasonable method of checking on the accuracy of observations. The AES Cartesian coordinates from the website of the International Laser Ranging Service (ILRS) [1] can be taken for such reference standard AES observations. The ILRS provides AES and lunar laser tracking data and related products to support geodetic and geophysical research activities. The website of the indicated service offers free access to the files with geocentric Cartesian coordinates expressed in the International Terrestrial Reference System (ITRS) for a certain list of AES [2]. The detailed information on satellites and their orbital elements is given at the ILRS website [3]. Information on the positions is given at the website in separate files for each satellite. Each laid up file contains geocentric Cartesian X, Y, Z coordinates of a particular AES for the current day when the file was created and the ephemerides for several subsequent days. Those coordinates are generated from the orbits obtained by a high-precision model of motion of AES (the Earth's gravitational field, air resistance (drag), solar radiation pressure, etc.). That is exactly why such Cartesian coordinates of AES can be used as reference standard ones. An example of the header of such a file is given in Fig. 1. More detailed information on the structure and format of the prediction file can be found at the website [4].

```
H1 CPF  1  HTS 2009  9 16 12  7591 ajisai          NONE
H2  8606101 1500    16908 2009 09 16  0  0  0 2009 09 21  0  0  0   240 1 1  0 0 0
H5  1.0100
H9
10 0 55089  85200.00000  0    5104060.378    4599246.690    3810782.560
10 0 55089  85440.00000  0    4666026.698    5712020.846    2715644.558
10 0 55089  85680.00000  0    4044116.477    6575900.301    1492264.912
10 0 55089  85920.00000  0    3258286.721    7156768.810     198465.511
10 0 55089  86160.00000  0    2335175.372    7433074.936   -1104701.959
10 0 55090      0.00000  0    1307254.820    7396585.330   -2355883.381
10 0 55090    240.00000  0     211730.692    7052513.897   -3496338.783
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Figure 1. The header of a part of the prediction file from the ILRS website.

The accuracy of the ephemerides in prediction files depends on the type of AES orbit. Taking into consideration the fact that prediction files contain ephemerides for several days, it is possible to determine the inherent accuracy of the ephemerides by comparing the files. Satellite Ajisay (altitude of about 1500 km) is taken as an example. The analysis of accuracy found that the inherent accuracy of positions in the file is about several meters for four days (Fig. 2). Such accuracy ensures an error in topocentric angular coordinates of about 0.5 arcsecond for the fourth day. Therefore, when using positions from the file only for the current day, it is possible to consider an error in coordinates themselves as negligible. It is evident that if the accuracy of observations themselves is less than 1 arcsecond, such an error should not be neglected. At the same time, it is not reasonable to consider that other satellites from the ILRS list have approximately the same accuracy. In that list, there are also satellites, orbits of which are regularly adjusted. The error curve for such satellites is to be more abrupt as the prediction files, generated before and after such an adjustment of orbit, are not comparable. For example, the ephemeris error for the Envisat satellite (altitude of about 700 km) is analyzed. The analysis showed that the ephemeris accuracy is admissible only for the current day when the file was generated. For the subsequent day the prediction accuracy is sharply worsening (Fig. 3).

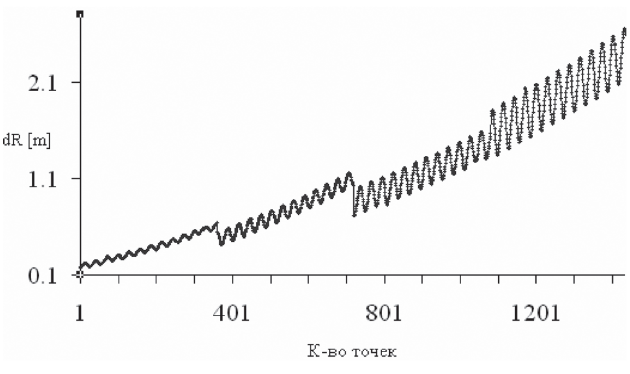

Figure 2. Inherent accuracy of the prediction files for Ajisay

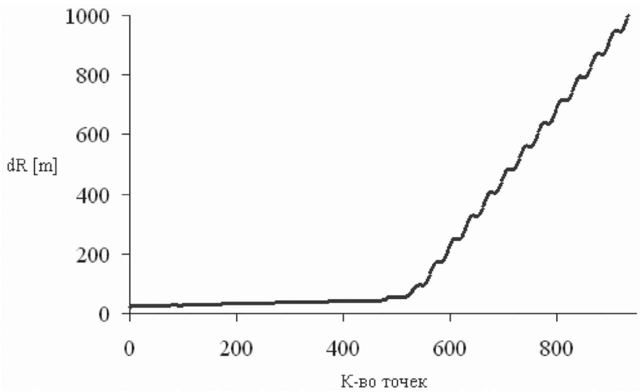

Figure 3. Inherent accuracy of the prediction files for Envisat

Stages of conversion of the ILRS positions to monitor the accuracy of observations

To be able to compare actual observations with reference standard ones, it is necessary to conduct a step-by-step conversion of both the ILRS positions and actual observations. It is indispensable as actual angular coordinates of objects turn out to be topocentric in the International Celestial Reference System (ICRS) for epoch J2000.0 as well. To get correct comparison, it is needed to convert the ILRS positions to the ICRS for epoch J2000.0.

Stage 1. As the Cartesian coordinates in the files are expressed in the ITRS, it is necessary to transform coordinates to the ICRS for epoch J2000.0. To do that, standard formulae for conversion of reference systems (1) can be used:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix}_{ICRS} = P' \cdot N' \cdot R_3(-S_{\oplus}) \cdot R_1(y_p) \cdot R_2(x_p) \cdot \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix}_{ITRS} \quad (1),$$

with P' – the precession matrix; N' – the nutation matrix; $R_3(-S_{\oplus})$ – the Earth rotation matrix; $R_1(y_p)$ – the matrix for clockwise rotation about the x-axis by empirical pole coordinate y_p; $R_2(x_p)$ – the matrix for clockwise rotation about y-axis by empirical pole coordinate x_p.

The time argument for the precession and nutation matrices is time referred to the Barycentric Dynamical Time (TDB) scale. The Earth rotation matrix represents the rotation about z-axis by angle equaled to the apparent sidereal time $S_{\oplus}$. The apparent sidereal time is a function of Universal Time $UT1$. Universal Time is obtained by adding the time correction ΔUT to UTC. It is recommended to use the algorithm for computing precession, nutation and rotation matrices for the apparent sidereal time as per formula (1) presented in the IERS Conventions (2003) [5. pp. 33-52]. The obtained AES position vector referred to the ICRS is used then to compute topocentric coordinates of the AES.

Stage 2. To compute the AES topocentric coordinates as per formula (2), the geocentric position of the observation station should be known:

$$\vec{r} = \vec{R} + \vec{\rho} \quad (2),$$

with $\vec{r}$ – the geocentric position vector of the AES; $\vec{R}$ – the geocentric position vector of the observation station; $\vec{\rho}$ – the topocentric position vector of the AES. It is possible to compute the observation station coordinates in the ITRS on having known its accurate latitude, longitude and elevation above sea level. When the station coordinates expressed in ITRS is known, they should be converted to the ICRS using the same formula (1). Then, using the obtained vector $\vec{\rho}$, it is possible to compute topocentric angular coordinates of AES by spherical trigonometry formulae.

Stage 3. Actual observations are usually obtained by image processing on video frames. There are many methods for processing of such data and extraction of the angular coordinates of the observed objects, for example [6]. Each frame is processed as a photographic plate. Referring to the coordinate system of a frame, the angular coordinates of the necessary object relative to reference stars in the frame are determined by the Turner's method. The peculiarity of such method of determination of the object's angular coordinates is that positions of the reference stars, caught in the frames, are taken from publicly-accessible high-precision star catalogues, such as Tycho and USNO catalogues. Those catalogues give the stars positions for epoch J2000.0 in the celestial coordinate system. Therefore, the objects angular coordinates, obtained by the method indicated above, are also turn out to refer to epoch J2000.0. However, as those observations are carried out from the Earth revolving around the Sun, the coordinates are distorted by annual and diurnal aberrations as well. To apply corrections for those aberrations, it is possible to use formula (3) to compute diurnal aberration and formula (4) to compute the annual one [7].

$$\begin{gathered}\Delta\alpha\cos(\delta) = 0^{s}.0213\cos(\varphi)\cos(t) \\ \Delta\delta = 0''.320\cos(\varphi)\sin(\delta)\sin(t)\end{gathered} \quad (3),$$

where φ - the astronomical latitude of the observation site; t – the hour angle.

$$\begin{gathered}\Delta\alpha\cos(\delta) = \frac{1}{c}\left[-\dot{X}\sin(\alpha) + \dot{Y}\cos(\alpha)\right] \\ \Delta\delta = \frac{1}{c}\left[\dot{Z}\cos(\delta) - \dot{X}\sin(\delta)\cos(\alpha) - \dot{Y}\sin(\delta)\sin(\alpha)\right]\end{gathered} \quad (4),$$

where c – the speed of light; $\dot{X}\ \dot{Y}\ \dot{Z}$ – components of the Earth Barycentric velocity in the Cartesian coordinate system; $(\alpha;\delta)$ – the object's equatorial coordinates in the ICRS.

As per description of the consolidated format of the ILRS files, the coordinates are given with no aberration corrections applied. Thus, to make a correct comparison, it is needed to apply corrections for annual and diurnal aberrations to the coordinates of actual observations.

Stage 4. Besides annual and diurnal aberrations, actual observations are distorted by planetary aberration as well. Moments of time, corresponding to the angular observations, should be corrected for planetary aberration. The value of aberration can be computed from the ILRS positions if the distance to the object and the speed of light are known.

Stage 5. As in the ILRS files of predictions all positions are given with a fixed step size of units of minutes, it is necessary to use the Lagrange interpolation method in order to obtain the ILRS coordinates for a certain instant of time from actual observations [8]. That method of interpolation is recommended for usage in the ILRS prediction format description [4]. It should be kept in mind that when interpolating coordinates at a certain instant of time from actual observations it is necessary to take into account the delay due to planetary aberration for that instant.

Testing the efficiency of the suggested method of monitoring the accuracy

The method of comparison of actual observations with the ILRS coordinate data has been implemented in the form of mathematical software. Using that, the analysis of the accuracy of the obtained actual observations of AES was conducted. To make such an analysis, the observation data for satellite Ajisay, obtained with telescope KT-50, are provided by Odessa Astronomical Observatory. The observations are in the equatorial coordinate system in arrays of points $(MJD;\alpha;\delta)_i$. The number of observation nights and points used for comparing with the ILRS coordinates are indicated in Table 1.

Table 1. Data on the observations analyzed

Observation date	Number of points
16.09.2010 – one pass	627
16.09.2010 – two passes	387
17.09.2010 – one pass	323
17.09.2010 – two passes	146
21.09.2010	353
23.09.2010	267

The error curves are output in the orbital coordinate system to make easier perception of graphs of difference between the observed and the computed positions (O-C). Therefore, on the (O-C) graphs, the satellite along-track error *dL* is displayed instead of right ascension error and the cross-track error *dH* – instead of declination error. The along-track error *dL* is given both in the angular measures and in the time scale, obtained using the satellite orbital velocity. On the following graphs, the x-axis shows the index numbers of points in the file containing actual observations. The (O-C) graph for the comparison of the first night observations is shown in Fig. 4.

the problem of delay in recording instants of time is of general type. The analysis of such a delay led to a conclusion that the delay value defines the CCD-matrix operating speed, used to obtain observations. A value of 10 ms is equal to a quarter of the frame, which is formed by a CCD-matrix with a frame frequency of 25 fps. Thus, by comparing actual angular coordinates with the ILRS positions, using the method indicated above, we succeeded in measuring and applying the CCD-matrix response time when forming the observations themselves. That allows of increasing the accuracy and quality of the observations obtained.

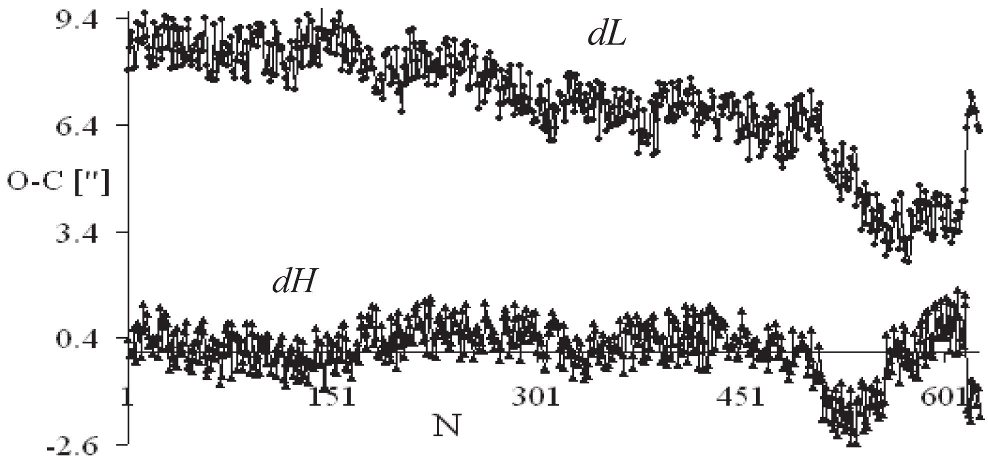

Figure 4. (O-C) observations on 16.09.2010 – one pass

As is evident from Fig. 4, the error curves are irregular due to the instruments operation when recording the observations. It is also clear that the error curve lies above the x-axis. That means that there is some problem in recording instants of time. Fig. 5 shows the along-track error *dL* in the time scale. On the average, the delay is about 10 ms. When that delay is considered in the instants of time of actual observations, then, as it is shown in Fig. 6, the (O-C) graphs are located along the x-axis as it should be. The analysis of the other observation nights demonstrated the same type of *dH* and *dL* error curves. That means that

Conclusion

The described method of monitoring the accuracy of observations using the ILRS coordinate data is relatively simple and enables to promptly conduct a check of the AES observations obtained. As the regularly-updated daily positions are provided for the satellites from the ILRS list, those are recommended to be used as reference standard ones to calibrate and monitor operation of observation instruments. Implementation of the suggested method enabled to determine for the first time the re-

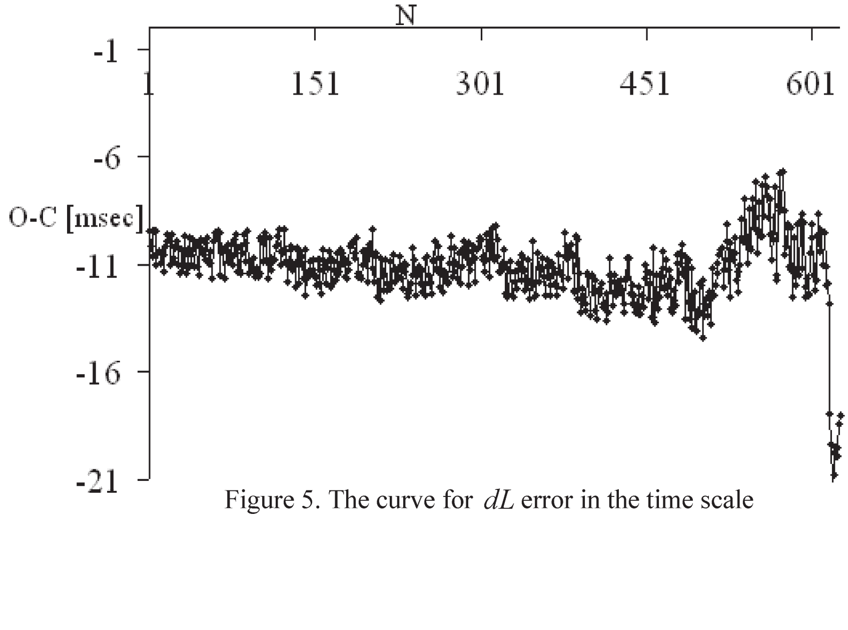

Figure 5. The curve for *dL* error in the time scale

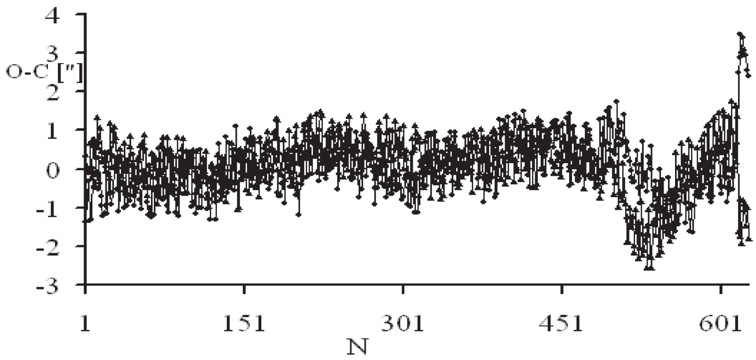

Figure 6. The curves for dH and dL track errors after adjustment of 10 ms

sponse time of CCD-matrices, used to obtain observations, and to apply that value when processing the observations of Odessa Astronomical Observatory. Moreover, the comparison with the ILRS data allowed of making the methods of processing the observations of Nikolaev Astronomical Observatory more precise [9] and of increasing the accuracy of their observations gathered. The leaders of both observatories made a decision to carry out regular observations of AES from the ILRS list in order to continuously monitor the observations obtained.

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