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Accuracy of orbits of small celestial bodies obtained using different software

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Abstract. The threat of a collision with a potentially hazardous object (PHO) and smaller asteroids requires the ability to reliably calculate the orbits of celestial bodies. The quality of the determined orbit depends on both the accuracy and intervals of observations and on the method of their processing: the completeness of the dynamic model, the method of numerical integration, calculation errors, etc. The practical implementation of the orbit determination algorithm is associated with the peculiarities of taking into account the above factors. To assess the accuracy of motion prediction using orbits obtained with the help of different software packages, we compared the deviations in observed and calculated values of observations, i.e. $O-C$, that were not included in the orbit improvement. The $O-C$ comparison was carried out for orbits obtained using software developed in leading Russian scientific organizations with teams working on asteroid-comet dynamics: Pulkovo, Tomsk State University (TSU) and Institute of Applied Astronomy of RAS (IAA), as well as orbits presented on the Jet Propulsion Laboratory's (JPL) Horizons website. The asteroids Apophis and Phaethon were chosen as objects for which the $O-C$ comparison was performed. Observations of each asteroid were divided into two samples by time. The asteroid's orbit was improved using the earlier sample, and the later sample was used to access the accuracy of the prediction. The $O-C$ distribution profile for orbits obtained using different software turned out to be very similar, indicating the proximity of predictions. The most accurate orbits were obtained using the `Improvement` and `IDA` software developed at the IAA and TSU, respectively.

Keywords: small celestial bodies; dynamics; orbit improvement; asteroid/comet hazard

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1 Introduction

At present, the problem of asteroid and comet hazard is given special attention. The number of potentially hazard asteroids has reached 2429 (as of July 29, 2024, IAU MPC[1]). Moreover, there is still a huge number of less bright asteroids with unknown albedo, which can also pose a danger to human safety (Reddy et al. 2024). These circumstances force us to predict the risks emanating from celestial bodies approaching the Earth, which is impossible to do without obtaining their high-quality orbits (Gehrels 1994). The accuracy of the orbit of a celestial body, i.e. predictions of its position at different moments in time, depends primarily on two components: the intervals and the accuracy of observations of the target body and the method of their processing which includes the completeness of the dynamic model, the accuracy of the transformation of coordinates between different reference systems, computational errors, rounding errors, etc. (Moyer 1971).

Today in Russia there are several software packages that allow us to determine the orbits of small celestial bodies and teams that are engaged in the development and maintenance of these programs. While developers are responsible for the quality of their software, it is necessary to have a one reference orbit in order to obtain a space threat assessment and the ability to respond in a timely manner. The aim of this work was to compare the accuracy of orbits obtained by different software available today.

For this purpose, we contacted members of research teams that study the dynamics of small celestial bodies, working in leading Russian research organizations. As a result, we could compare the orbits of the target bodies, obtained using programs developed at Tomsk State University (TSU), Central Astronomical Observatory of RAS at Pulkovo (Pulkovo), and Institute of Applied Astronomy of RAS (IAA). In total, we compared orbits obtained with four programs: `IDA` (TSU) (Galushina et al. 2021), `Baturin` (TSU), `Improvement` (IAA), `Lvov` (Pulkovo) and additionally the orbit taken from the NASA JPL Horizons website.

2 Method

To compare the accuracy of orbits obtained by different software, the asteroids Apophis (99942) and Phaethon (3200) were selected. We used positional and radar observations taken from the MPC and JPL[2] websites respectively. The observations were divided into two samples by time. The orbit of the celestial body was improved

[1] https://minorplanetcenter.net/
[2] https://ssd.jpl.nasa.gov/sb/radar.html

on the first, earlier sample, and the $O-C$ comparison (deviations between obtained and predicted values) was performed on the second, later sample.

As Kazimirchak-Polonskaya said, improving orbits is more art than science, which could be continued today—improving orbits is something akin to building neural networks, in the sense that there is a lot of uncertainty in this matter and the final result is influenced by the role of the researcher: in particular, how he weights the observations, what epoch he chooses to determine the orbit. Therefore, to reduce the role of the researcher in the process of obtaining an orbit, we fixed the epoch of improvement. The orbit was determined using the same set of observations for a given date within the sample for improvement. However, the assignment of weights to observations, the number of parameters to improve, and the force model used were left to the discretion of the researcher.

3 Results

Table 1 presents the root-mean-square (RMS) values of $O-C$ for right ascension (RA) multiplied by the cosine of declination (Decl), RMS $O-C$ values of declination (DEC) and the average values of $O-C$ deviations from zero (AV). The following notations are introduced here:

$$\mathrm{RA} = \sqrt{\frac{\sum[(O-C)_{\mathrm{RA}} \times \cos(\mathrm{Decl})]^2}{N}}; \quad \mathrm{DEC} = \sqrt{\frac{\sum(O-C)^2_{\mathrm{Decl}}}{N}};$$
$$\mathrm{AV} = \frac{\sum\sqrt{(O-C)^2_{\mathrm{Decl}} + [(O-C)_{\mathrm{RA}} \times \cos(\mathrm{Decl})]^2}}{N}, \tag{1}$$

where N denotes the number of observations.

3.1 Asteroid (99942) Apophis

The sample for improving the orbit of the asteroid Apophis consisted of 4469 positional and 46 radar observations during the 2004 and 2013 approaches. The error in presenting observations for all orbits obtained did not exceed 0.4 arcseconds. Since not all programs were capable of processing radar observations, we conducted a general comparison only on positional observations. The test sample consisted of 5061 observations during the 2021 approach. The epoch was taken at noon January 22, 2013. As an indicator of the accuracy of the predicted orbit, we calculated the deviations in $O-C$ from zero on the test sample. Fig. 1 shows the deviations in $O-C$ on the Apophis test sample for orbits obtained using different program software.

As one can see the $O-C$ distribution profile for all the orbits obtained turned out to be quite similar. The differences in the Keplerian elements between different

Table 1. Error in the representation of observations of the asteroids Apophis and Phaethon on the test sample. The first column contains the designation symbols for the software used to calculate the orbits. JPL denotes the orbit obtained from Horizons, IAA denotes the orbit obtained with the usage of `Improvement` software developed at IAA, `IDA` denotes the orbit obtained at TSU using the software package of the same name, BAT denotes the orbit obtained in TSU with A. Batrurin's software and PUL denotes the orbit obtained by V. Lvov from Pulkovo. The $O-C$ values for RA, DEC and AV are presented in arcseconds.

Designation	Apophis			Phaethon		
	RA	DEC	AV	RA	DEC	AV
JPL	0.601	0.589	0.559	0.348	0.467	0.297
IAA	0.794	0.602	0.794	0.349	0.469	0.303
IDA	1.144	0.655	1.150	0.324	0.276	0.279
BAT	1.239	0.687	1.263	0.686	0.329	0.691
PUL	2.640	1.099	2.663	0.434	0.498	0.418

orbits did not exceed: $de = 0.2 \times 10^{-6}$, $da = 0.2 \times 10^{-7}$ AU, $di = 0.2 \times 10^{-5}$ deg, $d\Omega = 0.7 \times 10^{-4}$ deg, $d\omega = 0.7 \times 10^{-4}$ deg. The minimal $O-C$ is for orbit taken from the Horizons website, since it was obtained from the entire set of observations, including observations from the test sample.

3.2 Asteroid (3200) Phaethon

The sample for improving the orbit of the asteroid Phaethon consisted of 5949 positional and 8 radar observations from 1983 to 2020. The error in presenting observations for most orbits did not exceed 0.4 arcseconds. The test sample consisted of 1524 positional observations during the 2020–2024. The epoch was taken at noon February 15, 2017. The $O-C$ distribution profile for all orbits also turned out to be quite similar. Fig. 2 shows the deviations in $O-C$ on the Phaethon test sample for orbits obtained using different software. The differences in the Keplerian elements between different orbits did not exceed: $de = 0.1 \times 10^{-5}$, $da = 0.1 \times 10^{-6}$ AU, $di = 0.5 \times 10^{-4}$ deg, $d\Omega = 0.2 \times 10^{-4}$ deg, $d\omega = 0.1 \times 10^{-3}$ deg.

4 Summary

This study was motivated by the growing interest in the problem of asteroid-comet hazard. In this work, we compared the accuracy of orbits obtained by different software developed by teams studying the dynamics of small celestial bodies. In order to ensure a unified response to a cosmic threat, it makes sense to have one or more reference orbits by which it would be possible to estimate the probability of collision with a celestial body.

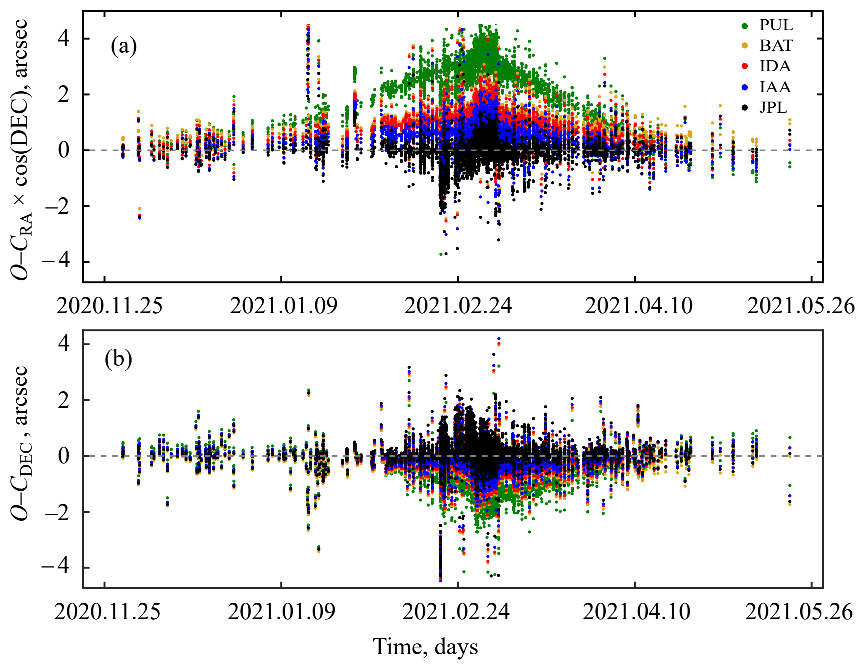

Fig. 1. Deviations in $O-C$ on the Apophis test sample for orbits obtained using different software.

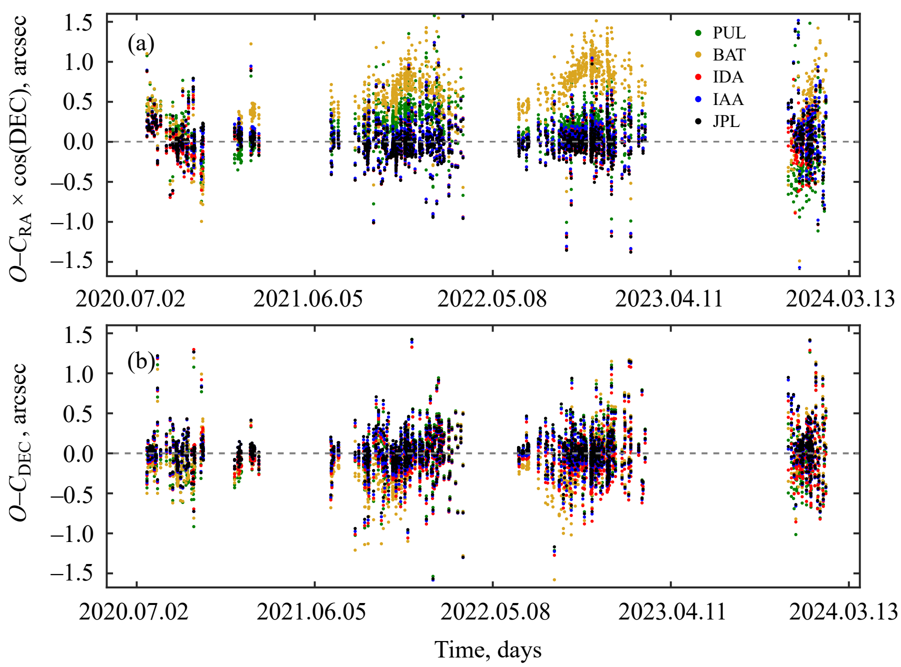

Fig. 2. Deviations in $O–C$ on the Phaethon test sample for orbits obtained using different software.

In this work, we compared orbits obtained by four programs developed at TSU, Pulkovo and IAA, as well as an orbit taken from the NASA Horizons. The accuracy of the orbits was estimated by the deviations in $O-C$ for observations not involved in the orbit improvement process. The asteroids Apophis and Phaethon were chosen as comparison objects. For the asteroid Apophis, the minimum average deviation of $O-C$ from zero was obtained for orbit calculated with the usage of `Improvement` software package developed in IAA. It amounted 0.794 arcseconds. The `IDA` software package developed at TSU was the best in predicting the orbit of asteroid Phaethon with an average $O-C$ deviation from zero of 0.279 arcseconds.

It should be noted that in order to obtain more accurate orbits, it is also necessary to process and correctly take into account radar and other types of observations in addition to positional ones, which are increasingly filling databases with observations of small bodies. It is especially important for near-Earth objects.

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