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TIME AND GEOLOCATION UNCERTAINTIES AS COMPONENTS OF THE ACCURACY OF NEAS' GROUND-BASED OBSERVATIONS

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ABSTRACT. The one of main tasks for solving the asteroid-cometary hazard problem is cataloging all objects that might come extremely close to Earth and pose a potential threat of collision. The reliability of their orbits significantly depends on the quality and the statistical treatment of astrometric observations, which are obtained by different observers and different techniques. Statistical analysis of the IAU MPC observational array of the small Solar system bodies and the development of a scheme for assigning weights to individual observation sets are important for performing asteroid orbit determination and refinement. Errors in the positions of asteroids associated with errors in the reference catalogs, observation epoch, observed brightness and rate of motion are considered in sufficient detail in investigations of Chesley et al. (2010), Farnocchia (2015), Vereš et al. (2017). Timing and geolocation uncertainties of the observer are less discussed in the literature. But in the case of observations of NEAs, especially at the moments of the close approaches to the Earth, timing errors and errors in the observatory's geolocation can significantly affect the accuracy of the obtained positions. Residual differences (O - C) in the equatorial coordinate system are usually used to search and identify functional errors dependencies. To detect errors caused by timing uncertainties, instead of residual differences (O - C) in equatorial coordinates, it is more convenient to use their along-track and cross-track representation. The cross-track differences are independent of timing errors and indicate only astrometric errors. On the other hand, timing errors are fully contained in the along-track component.

Here we present the simulation results of such errors and analysis using an array of observations from three observatories for the period 2017 - 2022. The array contains more than 18,000 positions of about 900 objects. Most of the objects belong to the group of NEAs, which include PHAs during close approaches to the Earth.

Keywords: astronomical databases, astrometry, positional errors, near-Earth asteroids.

АНОТАЦІЯ. Одним із головних завдань вирішення проблеми астероїдно-кометної небезпеки є каталогізація всіх об'єктів, які можуть наблизитися до Землі надзвичайно близько і становити потенційну загрозу зіткнення. Надійність їх орбіт суттєво залежить від якості та статистичної обробки астрометричних спостережень, які отримують різні спостерігачі з застосуванням різноманітних методів спостережень. Статистичний аналіз масиву спостережень малих тіл Сонячної системи МАС ЦМП та розробка схеми призначення вагових коефіцієнтів окремим серіям спостережень є важливими для визначення та уточнення орбіти астероїдів. Похибки в положеннях астероїдів, що пов'язані з похибками в опорних каталогах та залежать від епохи спостережень, яскравості і швидкості руху об'єкта досить докладно розглянуті в роботах Чеслі та ін. (2010), Фарночча (2015), Верес та ін. (2017) та ін. Менше обговорюється в літературі похибки, що пов'язані з невизначеністю часу та геолокацією спостерігача. Але у випадку спостережень навколоземних астероїдів (НЗА), особливо в моменти близьких наближень до Землі, похибки синхронізації часу та похибки геолокації обсерваторії можуть істотно вплинути на точність отриманих топоцентричних положень. Залишкові різниці (О - С) в екваторіальній системі координат зазвичай використовуються для пошуку та ідентифікації залежностей функціональних помилок. Для виявлення помилок, викликаних невизначеністю часу, замість залишкових різниць (О - С) в екваторіальних координатах зручніше використовувати різниці (О - С) вздовж та перпендикулярно напрямку руху об'єкта спостереження. Поперечні різниці не залежать від похибок синхронізації часу та визначаються позиційною похибкою спостережень. З іншої сторони, похибки синхронізації часу повністю містяться в компоненті уздовж траєкторії руху об'єкта.

Тут ми представляємо результати моделювання та аналіз таких похибок з використанням масиву спостережень трьох обсерваторій за період 2017–2022 рр. Масив містить понад 18 000 положень приблизно 900 об'єктів, більшість з яких є НЗА. включаючи потенційно-небезпечні астероїди (ПНА), протягом періодів близьких наближень до Землі.

Ключові слова: астрономічні бази даних, астрометрія, позиційні помилки, навколоземні астероїди.

1. Possible impact of geolocation and timing errors

The one of main tasks for solving the asteroid-cometary hazard problem is cataloging all objects that might come extremely close to Earth and pose a potential threat of collision. The reliability of their orbits significantly depends on the quality and the statistical treatment of astrometric observations, which are obtained by different observers and different techniques. To improve the accuracy of the orbits, it is necessary to know the nature of the astrometric errors in NEAs observations. The main components of these errors usually include errors in the determination of the centroid and errors in the reference catalogue (both positions and proper motions). A number of investigations are devoted to the study and identification of such errors in the MPC database (Chesley et al., 2010; Farnocchia, 2015; Vereš et al.; 2017; etc.). The development of highly sensitive techniques (CCD and CMOS detectors) for object registration and creation of the accurate Gaia mission catalogs have led to a significant improvement in the positional accuracy of ground-based observations. However, in the case when we deal with objects that move at high apparent rates of motion, errors associated with the uncertainties of the time moment and the position of the observer can play a decisive role. The importance of taking them into account for obtaining homogeneous data arrays during large observational campaigns of individual objects, such as *2019 XS*, *2012 TC4*, and *Apophis (99942)* observations, was also discussed in the literature (Reddy et al., 2019; Farnocchia et al., 2015, 2022; Thuillot et al., 2015). Since these errors also become significant as asteroids approach the Earth, NEA observations during close approaches to the Earth are convenient observational material for searching for such errors.

1.1. Timing Errors

To identify possible errors associated with the synchronization of observation time, it is convenient to pass from residual differences (O - C) in equatorial coordinates to differences in along- (AT) and cross-track (CT) representation to the object's apparent trajectory motion. The CT residuals will depend only on the measuring procedure and indicate the internal accuracy of the observations. While the errors associated with the moment of time will be completely included in the AT component. Obviously, its value will depend on the rate of motion of the observed object:

$$(O-C)_{AT} \approx \Delta t \cdot V,$$

where $(O-C)_{AT}$ – along-track difference (O - C); Δt – timing error; V – asteroid's apparent full rate.

1.2. Geolocation Errors

When observed objects are at close distances to Earth, inaccurate or erroneous determination of the coordinates of the observation site can also be a source of important systematic errors in the topocentric positions of the asteroids. These errors can reach significant values for objects at extremely close distances to Earth.

As shown in Thuillot et al. (2015):

$$\theta \approx \frac{\Delta \cdot 206265}{x},$$

where θ – the difference in the astrometric position in arcsec; x – distance between observer and asteroid; Δ - distance between real and accepted geolocation.

In the report, based on the original observations of three observatories, we will show how timing and geolocation uncertainties could affect the accuracy of obtained topocentric positions.

2. Input Array: telescopes, statistics

2.1. Telescopes and observational technique

Observations from three observatories, which carry out regular observations of near-Earth asteroids, were chosen as an input array for simulations of time and geolocation uncertainties. Mykolaiv (MPC code 089) and Lishan (O85) observatories implemented a special technique (RDS CCD technique) for observing asteroids with high apparent rates of motion, which makes it possible to obtain observations of program objects at close distances from Earth with good positional accuracy. The main feature of the RDS CCD technique is the usage of a rotational platform and TDI mode of CCD to obtain separate CCD frames both for reference stars and objects which have a high apparent rate of motion (Tang et al., 2014; Pomazan et al., 2021) with different exposure time. Telescopes are equipped with GPS receivers. This allows us to assume that the moment of observation time for these observational arrays is determined with an accuracy of no worse than 0.1^s. Observations by Zalisci station (L18) are performed in the sidereal tracking mode, with the use of the "shift-and-stack" method for processing observations of relatively faint objects. The observations used in this paper were obtained with two telescopes: 0.3-m f/1.0 and 0.5-m f/3.8. Despite the fact that the first telescope began observations in 2017 (Maigurova et al., 2017) and the second one only in the middle of 2020, the bulk of the observations was carried out with the second telescope. The timing accuracy of L18 observations was also no worse than 0.1^s, except for a few cases with large errors caused by camera control software failure.

Instrumental characteristics of the telescopes used for observations are presented in Table 1.

2.2. Observations

The array of observations for the period 2017 -2022 (as of July 2022) was selected as the initial array for further simulation. The array contains over 18,000 positions of 885 asteroids. Most of the objects belong to the group of NEAs, which include PHAs, during close approaches to Earth. The observation array of 089 contains both fast-moving objects from the NEA group and asteroids from the Main belt. 22 (8%) NEAs from 089's array has full rate ≥ 40"/min during observations. The arrays of observations performed by L18 and O85 observatories include only NEAs. The part of fast-moving NEAs there is 12% and 18%, respectively for L18 and O85. Some objects were observed at very close distances from the Earth with extremely high apparent rates of motion, such as *2020 RZ6* (apparent rate in right ascension (RA) -95"/min, in declination (DE) -209"/min), *2020 DD0* (-508"/min and 15"/min), *2021 CO0* (-343"/min and -178"/min, correspondingly in RA and DE). Statistical characteristics of input arrays are presented in Table 2. Column **N1** in Table 2 represents the number of obtained positions, and **N2** – the number of asteroids.

Table 1: Technical specifications of the telescopes

Telescope	Lishan (O85)	Mykolaiv (089)	Zalisci (L18)
Diameter, m	0.5	0.5	0.3/0.5
Focal length, mm	3445	2975	300/1900
CCD	Alta U9000		ZWO ASI-174M Cool/ FLI ML16070*
Size, px	3056 x 3056		1936 x 1216 / 2432 x 1616*
Pixel size, μm	12 x 12		5.86 / 14.8*
Scale, ″/px	0.72	0.83	4.0/1.7*
FOV, ′	36.7 x 36.7	42.5 x 42.5	130 x 80 / 64.8 x 43
Filter	no	V*	no

* – Observations were carried out in the 2x2 binning mode.

Table 2: Statistical characteristics of the input array

Obs. Code	**N1**	**N2**	**O – C***	
			RA, mas	**Dec, mas**
089	9286	263	21±121	34±196
L18	6777	654	9±378	4±377
O85	2175	97	-2±157	-0±153
All	18238	885**	15±276	19±295

*residual differences (O – C) between observed data and HORIZONS online ephemeris service

**The actual number of objects may be less due to the observation of the same asteroids in different observatories

3. Simulation technique and results

To investigate how possible time and geolocation uncertainties can distort observational data, simulations of such errors were modeled on the input array of original observational data. The ephemerides for the true and shifted time moments were obtained using the HORIZONS online ephemeris service for timing errors simulation. Then the residual differences (O - C) were calculated in the expansion in equatorial coordinates and as AT and CT representation. To calculate the AT and CT differences, the equatorial coordinate system was rotated to alight the equator plane with the trajectory of an object's apparent motion trajectory. To eliminate possible curvation, the rotation angles were calculated based on consecutive ephemeris positions for the time moment of observations. Simulation data in the form of residual differences (O - C) in equatorial coordinates and AT/CT components are shown in Table 3. As can be seen from Table 3, with the usage of equatorial differences (O - C), timing errors of 0.5-1^s can be revealed only in the case of high-precision observations, when the part of objects with high apparent rates is sufficiently large, as in the case of O85's data. However, these errors become easily noticeable when passing from equatorial differences to differences in along-/cross-track projections to the object's motion trajectory. Figure 1 shows the mutual distribution of the equatorial differences (O - C) and differences for AT/CT representation for the initial array and for the case when the timing uncertainty is 1^s.

Another type of errors that can distort the accuracy of NEA positional observations is erroneous coordinates of the observation site. Since the uncertainty in the coordinates on the Earth's surface in most cases is much less than the distance to the celestial object, the significant influence of this error can only manifest itself when observing objects are at extremely close distances to Earth. In this case, even an error of several hundred meters will contribute a notable systematic component to the total observational error. To assess the influence of incorrect geolocation coordinates on the obtained topocentric positions, the residual differences with the ephemeris from HORIZONS online system, which were obtained for shifted site coordinates, were calculated. For simulation, the site coordinates for 089, L18 and O85 observatories were shifted in longitude and latitude by given values. For further calculations, only observations at a distance of less than 0.05 AU were selected (3019 positions of 294 asteroids). The simulation results are shown in Table 4, where Δ is the difference together in longitude and latitude between currently accepted and erroneous geographic coordinates. Of course, for modern ground-based observations, the 600" error seems unlikely, and the data in the last row are given only for a clearer visualization of the effect of geolocation uncertainties on topocentric positions of NEAs.

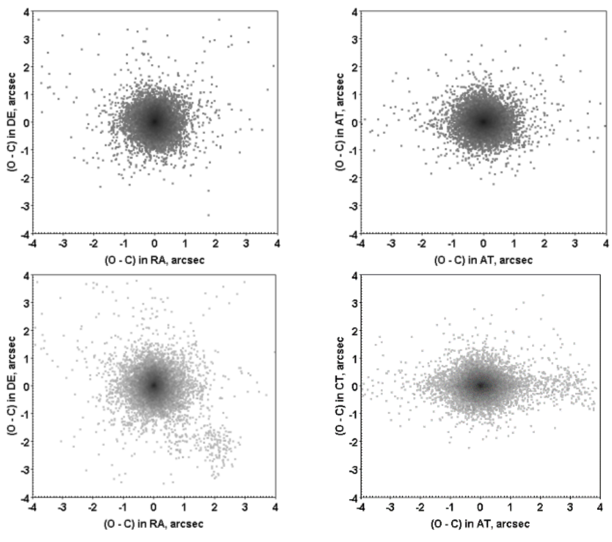

Figure 1: Mutual distribution of (O - C) differences in the equatorial coordinate system (left panels) and in AC/CT representation to object's trajectory (right panels) for original data array (top panels) and with 1^s timing uncertainty.

Table 3: The simulation results of timing errors for data arrays of considered observatories.

Observatory, MPC code	Δt, sec	(O - C), mas			
		Ra	Dec	AT	CT
089	Initial	21± 121	34 ±196	25± 172	22 ±155
	0.5	17± 157	33 ±225	20 ±228	22± 155
	1.0	13± 218	32 ±282	15 ±322	22 ±155
	2.0	5 ±350	30 ±418	7± 523	21± 155
	5.0	-17 ±803	25 ±921	-21 ±1213	22 ±155
	10.0	-55 ±1570	16±1790	-66 ±2377	22 ±155
L18	Initial	9± 377	4 ±377	20 ±423	5 ±312
	0.5	14± 516	3 ±465	23 ±616	7± 321
	1.0	15 ±624	-13± 576	22± 787	7 ±321
	2.0	19± 916	-43± 867	21 ±1221	8± 321
	5.0	29± 2053	138 ±1965	18± 2829	8 ±321
	10.0	48 ±4039	-297± 3868	12 ±5594	8± 321
O85	Initial	-3 ±155	2 ±151	-3 ±187	-5± 118
	0.5	21 ±394	5± 267	28 ±471	-5 ±118
	1.0	44± 726	13 ±449	59± 864	-5± 117
	2.0	88± 1356	27±809	116± 1607	-5 ±117
	5.0	227 ±3377	72± 1981	298 ±3995	-5 ±115
	10.0	88 1356	-	-	-

Table 4: The simulation results of geolocation uncertainties for observations, when the distance to Earth was less than 0.05AU.

Δ	(O - C), mas			
	RA	DE	AT	CT
0	7 ±597	60± 505	49 ±697	12 ±356
20"	52 ±598	100 ±506	73± 699	42 ±363
60"	144± 619	181 ±520	119 ±719	103± 406
600"	642 ±1378	591±1269	347 ±746	432± 929

As can be seen from Table 4, the incorrect observer coordinates will introduce a systematic error in the residual differences (O - C), which can appear even with relatively small inaccuracies in the position of the observer, for example, when several telescopes have the same MPC code. The dependencies of the residual differences vs distance of the object from Earth are shown in Figure 2.

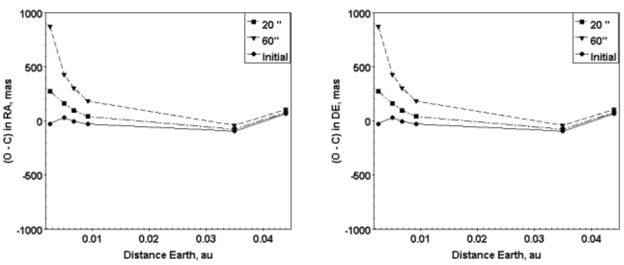

Figure 2: The dependency of positional accuracy of NEAs regarding to their distance from Earth for simulation of geolocation uncertainties based on observational data with objects' distances from the Earth less than 0.05 AU.

4. Conclusion

Timing errors can be easily detected by analyzing the residual differences (O - C) as along- and cross-track components. Simulation has shown that timing uncertainties of 0.5–2^s are not valuable when positional accuracy is worse than 0.2" for Main belt asteroids and slow-moving NEAs, but fast-moving objects (with rates of apparent motion more than 2"/min) needs time accuracy of at least 10^{-6} day (a large part of MPC observations has 10^{-5} day).

For the reveal of systematic timing errors, the analysis of the errors of individual sets of observations is required.

Geolocation uncertainties begin to affect the accuracy of observations of asteroids only at very small distances from Earth. To detect them, it is necessary to analyze the dependence of the total observation errors vs the distance between the observer and the asteroid.

In the future, it is planned to analyze close approach observations from the MPC array to detect such errors in observations from different locations.

References

Chesley S.R., et al.:2010, *Icarus*, **210**, 158.
Farnocchia D., et al.: 2015, *Icarus*, **245**, 94.
Farnocchia D., et al.: 2019, *Icarus*, **326**, 133.
Farnocchia D., et al.: 2022, PSJ, **3**, id. 156.
Maigurova N., et al.: 2017, *BKNUA*, **2** (56), 22.
Pomazan A., et al.: 2021, *RAA*, **21**, 175.
Reddy V., et al.: 2019, Icarus, **326**, 133.
Tang Z.-H., et al.: 2014, *Mem. Soc. Astron. Italiana*, **85**, 821.
Thuillot W., et al.: 2015, A&A, **583**, id. A59.
Vereš P.: 2017, Icarus, **296**, 139.
Vereš P., Payne M. J., Holman M. J., et al.: 2018, *AJ*, **156**, 5.