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HIGH-PRECISION FOLLOW-UP OBSERVATIONS OF NEAR-EARTH OBJECTS

N.V. Maigurova, A.V. Pomazan, A.V. Shulga

Research Institute “Mykolaiv Astronomical Observatory”, Mykolaiv, Ukraine
nadija@mao.nikolaev.ua

ABSTRACT. Main objective of the study is orbit refinement of Near-Earth Objects (NEOs) as part of the global task of asteroid-cometary hazard. We present the latest results of ongoing high-precision astrometric follow-up observations of NEOs using the Mykolaiv Observatory KT-50 telescope of Mobitel Complex that equipped Alta U9000 CCD camera. Main feature of the objects of this study is the fast moving in the field of view. That circumstance makes impossible to observe NEOs as point images and to obtain their precise coordinates by the classical methods of observation. We used modified Rotating-drift-scan CCD mode for obtaining NEOs images and classical mode – for obtaining fields with reference stars to carry out astrometric reductions. The combination of classical and modified observational modes allows us to recover objects having $V < 17$ with high astrometric precision. The comparative statistics of Mykolaiv observations of NEOs for the period 2015-2018 and analysis of positional accuracy are presented. The results of the effect of new observational data on the residual differences (O-C) in both coordinates with respect to HORIZONS JPL ephemerides are shown on examples two potentially-hazard asteroids (2001KB67 and 2017YE5) during their close approaching to Earth in 2018. It is shown that adding new observations can significantly improve the accuracy of determining the orbital elements of such objects.

Keywords: CCD observations, asteroid-cometary hazard, NEOs (near-earth asteroids), PHAs (potentially hazard asteroids), ephemerids of small Solar system bodies.

АБСТРАКТ. Основною метою дослідження є уточнення орбіти об'єктів, що зближуються з Землею (АЗЗ) в рамках глобальної задачі астероїдно-кометної небезпеки. Ми представляємо останні результати алертних високоточних астрометричних спостережень АЗЗ, що отримані за допомогою телескопу КТ-50 комплексу Мобітел Миколаївської обсерваторії, обладнаного ПЗЗ-камерою Alta U9000. Основна особливість об'єктів цього дослідження – це швидке переміщення в полі зору, що робить неможливим отримання точкових зображень та точних координат таких АЗЗ класичними методами спостереження. Ми використовували комбінований режим синхронного переносу заряду з поворотною платформою для отримання зображень АЗЗ та класичний режим – для отримання полів з опорними зірками для подальшого виконання астрометричних редукцій. Поєднання

класичного та комбінованого режимів спостережень дозволяє нам спостерігати об'єкти до 17 зоряної величини (у фільтрі V) з високою астрометричною точністю. Наведено порівняльну статистику Миколаївських спостережень АЗЗ за період 2015-2018 рр. та аналіз позиційної точності. Результати впливу нових даних спостережень на остаточні різниці (O-C) за обома координатами по відношенню до HORIZONS JPL ефемериди показані на прикладах двох потенційно-небезпечних астероїдів (2001KB67 і 2017YE5) під час їх зближення з Землею у 2018 році. Показано, що додавання нових спостережень може значно підвищити точність визначення елементів орбіт таких об'єктів.

Ключові слова: ПЗЗ-спостереження, астероїдно-кометна небезпека, АЗЗ (астероїди, що зближуються з Землею), ПОА (потенційно-небезпечні астероїди) ефемериди руху малих тіл Сонячної системи.

1. Introduction

Ground-based optical position observations of the solar system bodies are the basis for creation of the motion theories, defining and clarifying of the orbits elements and dynamic parameters. Regular observations of near Earth objects (NEOs) are also one of the most important aspects of studying the problem of asteroid-cometary hazard and allow us to do refinement of the orbits, which makes it possible to predict a collision of a quite large body with the Earth in future and to take appropriate measures in advance. The maximum close approach period with the Earth is most favorable for the search of small-scale NEOs because at another time they have rather weak magnitudes and inaccessible to observations even at large telescopes. Much of them belong to the class of potentially-hazard asteroids (PHAs). Fig. 1 shows the distribution of the all known PHAs apparent magnitudes at discovery data (Asteroid list was taken from <https://www.minorplanetcenter.net/iau/lists/PHAs.html> at the beginning of 2018). Apparent magnitudes were calculated with on-line service HORIZONS JPL ephemeris (<https://ssd.jpl.nasa.gov/horizons.cgi>).

The problem of asteroid-cometary hazard is one of the priority tasks around the world. NEOs can pose a threat to existing spacecraft, as well as to the population of the Earth as a whole. Nowadays, many scientific projects, which are allocated significant funding, are engaged in monitoring of known NEOs and the search for new ones.

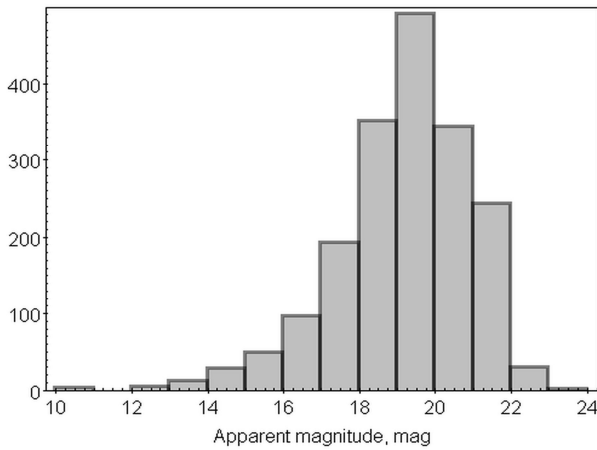


Figure 1: NEOs apparent magnitude on discovery data

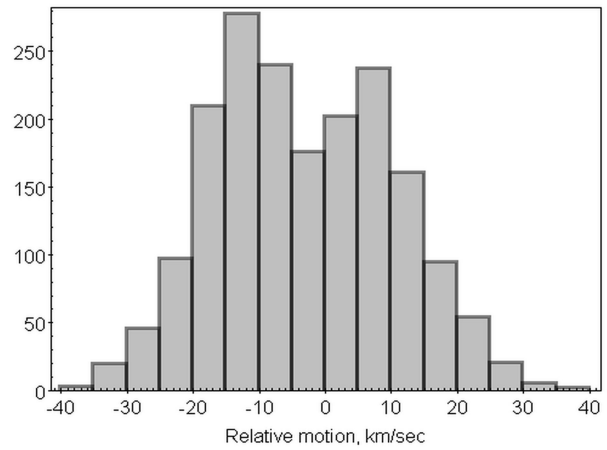


Figure 2: NEOs relative motion on discovery data

The most active project in the field of the search and observations NEOs in the optical range are Pan-Starrs (Wainscoat et al., 2018) and Catalina sky survey (CSS) (Leonard et al., 2017). But despite the efforts being made in this direction, this task cannot be considered solved. Fig. 2 shows the histogram of the distribution of the NEOs versus the relative motion of approaching the Earth on the discovery date of these bodies. The range-rate ("delta-dot") parameter from JPL's HORIZONS ephemeris is used as relative motion. A positive "del-dot" means the NEO is moving away from the Earth, a negative "del-dot" means the NEO is moving toward the Earth. As you can see from Fig. 2 more than 40% of known NEOs were discovered after they had approached to a minimum distance to the Earth. This proves the importance of regular monitoring of the hazardous celestial objects on the approach way to the Earth.

The observations of NEOs on the close distances from the Earth with classic methods is becomes complicated, since their apparent velocity in the field of view may be in the range of 0.2" to 120" per minute and even more. An original combined observation method, the main feature of which is the separate obtaining of images of reference stars by classical drift-scan mode and fast moving bodies with using Rotating-drift-scan CCD is realized in the Mykolaiv Observatory for the positional observations of celestial bodies with high apparent motions. Using Combined observation method allows to get all the images as a point, that in turn to determine the coordinates of the center of the image with maximum accuracy.

2. NEOs Asteroid Observations and Reductions

The array of NEOs CCD observations obtained on the telescope KT-50 of the Mobitel complex RI "MAO" was used to perform astrometric reductions by combine scheme with one of the modern astrometric catalogues (Maigurova et al., 2017). We used UCAC3, 4 catalogues previous to GAIA data release catalogues become available. Mobitel complex is operated for observations since 2011. The telescope KT-50 (F = 3000mm, D = 500mm) is equipped with Alta U9000 camera (3Kx3K, 12x12mkm, 42.5'x42.5' FOV, 0.83"/pixel) in photometric band OG-14 (near standard Rc band). Since 2017 telescope was equipped by standard V filter in Johnson system. The more detailed description of the complex is given in (Shulga et al., 2012). As mentioned above, images with reference stars and NEOs obtain separately. The time exposure for star images is 10 sec. It depends from the expected stellar magnitude for NEOs images and typically exposure time ranges from 60 to 150 seconds. The processing of the stars images was carried out by the package "Astrometrica" (<http://www.astrometrica.at>) in automatic mode. The detailed description of the reduction pipeline is given in (Sibiryakova et al., 2015). Statistics of the NEOs Mykolaiv observations with MPC code 089 during 2015–2018 are shown in Table 1, where N1, N2 – number of obtained positions and asteroids, correspondingly; n1, n2 – number of the positions and asteroids for new objects, which were discovered in the current year. Table column "residuals" are given (O–C) differences with NEODYs-2 ephemeris (<http://newton.dm.unipi.it/neodysl/>) and their RMS.

Table 1: NEOs observations of the RI "MAO" (MPC code 089)

Year	N1	N2	Current year		Residuals, mas			
			n1	n2	RA	RMS	DE	RMS
2015	742	50	286	21	16	323	74	368
2016	172	19	39	6	-2	258	135	379
2017	695	32	246	12	-20	214	71	258
2018*	633	28	36	3	30	217	42	288
All	2242	123	607	42	7	260	68	317

*As of beginning of October

It should be noted that despite the fact that the technical capabilities and weather conditions of our observatory are much worse than those of large survey projects, for some objects our observations make up a significant proportion of all available observations. Usage the combined method gives us the opportunity to observe the approaching object among the first on the current orbit turn. Statistics of the selected PHAs is given in Table 2, where N, % mean number of Mykolaiv observations and their part from all MPC observations for these objects, Mag – mean apparent magnitude. As can be seen from the Table 2 some potentially hazardous asteroids have only a few dozen observations and our share is over 10%.

Table 2: Statistics of the selected PHAs

NEO	N	%	Residuals \pm RMS, mas		Mag
			RA	DE	
1999KW4	78	20	45 \pm 148	116 \pm 138	14.0
2015LG2	24	16	47 \pm 275	207 \pm 302	17.5
2001KB67	46	14	155 \pm 115	146 \pm 212	15.2
2017NS5	20	12	370 \pm 153	-93 \pm 271	16.2
2017MB1	41	9	-190 \pm 193	-27 \pm 265	15.6
2010NY65	32	7	23 \pm 198	213 \pm 211	16.8
2017YE5	19	6	131 \pm 178	11 \pm 242	15.6
2011UW158	52	6	-6 \pm 321	110 \pm 347	16.0
2015DP155	38	6	-33 \pm 174	5 \pm 378	15.3
2018EJ4	19	4	-2 \pm 138	176 \pm 225	15.6

3. Accuracy Analysis

As can be seen from Table 1 during 2015–2018 we have obtained 2242 positions for 123 NEOs. This number is less than sum for column 2 because we observed some asteroids during several periods of visibility, which belong to different years. The duration of a series of frames of one object usually didn't exceed 30 minutes, so the positions of the object in a series of frames were calculated with fixed set of reference stars on a small arc of the orbit. These circumstances make possible to use the mean square error (RMS) of the residual differences (O–C), where (O) is the position obtained from the observations, (C) – the ephemeris position at the time of observation, as an estimate of the intrinsic precision of our measured positions. Fig. 3 shows these errors in both right ascension and declination for a single observation plotted against apparent magnitude.

As can be seen from Fig. 3 and Table 1, precisions of NEOs Mykolaiv observations is high enough for this kind of objects. The rotation-drift-scan CCD mode allows us to observe NEOs with large velocity, when they have maximum brightness. Part of our observations 2017 have index "h – high accuracy" according MPC statistics (<http://www.minorplanetcenter.net/iau/special/residuals.txt>).

It is worth noting, that much of NEOs are potentially-hazardous objects that approach the Earth at a distance of less than 0.05 AU and have an absolute stellar magnitude of less than 22^{mag}. A detailed analysis of the 2018 observations for two of them is given below.

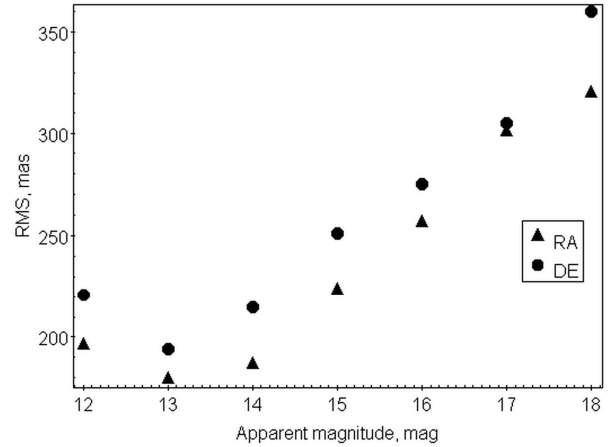


Figure 3: RMS on right ascension (up) and on declination (down) versus asteroid apparent magnitude

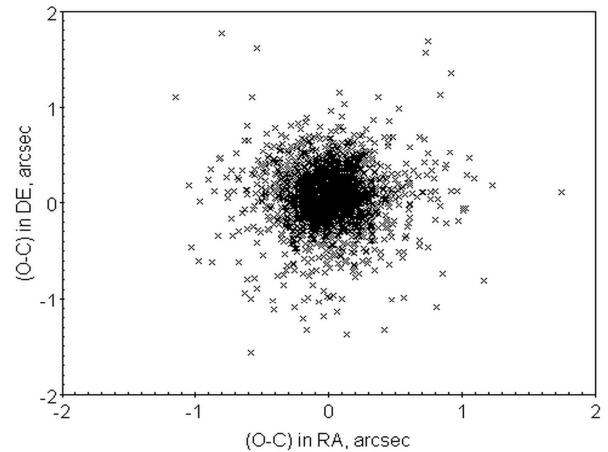


Figure 4: The mutual distribution of residual differences (O–C) in right ascension and declination

The mutual distribution of residual differences (O–C) in right ascension and declination are shown in Fig. 4. Only 2% residuals exceeded the value 1".

3.1. 2001 KB67 (68347)

Asteroid was discovered by LINEAR project on 2001, May 30. Close approach to Earth to 0.024 AU was at 2018, May 29. There were 228 observations with not good accuracy obtained for 2001–2017 period before 2018 observation campaign. The mean residuals differences (O–C)_{ra,de} were (0.01 \pm 0.74)" and (0.13 \pm 0.58)". 309 positions were obtained by 24 observatories during 2018 visibility period. The mean residuals differences (O–C)_{ra,de} for them are (-0.01 \pm 0.33)" and (-0.02 \pm 0.33)".

The Table 3 gives results of comparison 2 series of the Mykolaiv observations (MPC code 089) with JPL ephemeris on date observation (1) and after adding new 2018 observations (2).

3.2. 2017 YE5

Asteroid 2017 YE5 was discovered on 2017, December and approached Earth within 0.04 au on 2018, June 21. The orbit of 2017 YE5 has a Tisserand parameter of 2.875, which is possibly point the object could be an extinct Jupiter-family comet. Only 95 observations were available until 2017 YE5 was approached Earth. Tab. 4 is shown values of the residuals differences (O–C) for the Mykolaiv observations (code 089) with JPL ephemeris, which calculated on June 21(1) and after this date (2), when new observations were added.

Table 3: 2001 KB67 (O–C) differences (MPC code 089)

Date 2018.05	(O-C) (1)		(O-C) (2)	
	RA	DE	RA	DE
29.028813	3.08	0.99	0.67	-0.23
29.031136	2.81	0.9	0.40	-0.33
29.033463	2.74	1.27	0.34	0.04
29.035789	2.71	1.04	0.30	-0.19
Mean	2.83	1.05	0.43	-0.18
RMS	0.17	0.16	0.17	0.16
31.003218	-0.19	1.82	0.23	0.12
31.005547	-0.31	1.71	0.12	0.00
31.007874	-0.21	1.57	0.21	-0.14
31.010201	-0.05	1.50	0.37	-0.20
31.012539	0.10	1.59	0.53	-0.11
31.014866	-0.10	1.57	0.34	-0.13
31.017216	-0.08	1.69	0.36	-0.02
31.019554	-0.10	1.59	0.34	-0.10
Mean	-0.12	1.63	0.31	-0.07
RMS	0.12	0.10	0.13	0.10

Total were received new 241 positions for 2017YE5, which made it possible to significantly improve the accuracy of the orbit and successfully conduct radar observations of this asteroid. The mean residuals differences (O–C)_{ra,de} for them are (-0.08±0.39)'' and (-0.04±0.48)''.

Table 4: 2017YE5 (O–C) differences (MPC code 089)

Date 2018.06	(O-C) (1)		(O-C) (2)	
	RA	DE	RA	DE
20.966624	-10.67	-7.23	-0.14	0.01
20.971275	-10.57	-7.07	-0.04	0.17
20.981830	-10.33	-7.52	0.20	-0.27
20.987260	-10.43	-6.84	0.09	0.43
20.989585	-10.29	-6.99	0.22	0.28
Mean	-10.43	-7.21	0.09	0.04
RMS	0.15	0.31	0.15	0.31

4. Conclusions

In this paper, the results of ongoing observations of NEOs using the Mykolaiv Observatory KT-50 telescope of Mobitel Complex are presented. 2242 positions of 123 NEOs were obtained during last 4 years. The using rotation -drift -scan CCD mode allows us to observe the fast moving asteroids with high accuracy. It was shown also that adding new observations can significantly improve the accuracy of determining the orbital elements of potentially hazard asteroids.

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