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ONGOING FOLLOW-UP NEA OBSERVATIONS IN UKRAINE AND CHINA USING RDS CCD TECHNIQUE

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ABSTRACT. The current state of near-Earth asteroids (NEAs) observations shows an annual increase in the number of newly discovered objects. However, the frequency distribution of NEAs by size shows a sharp decrease in the number of objects with size less than 300 m, which contradicts the results of theoretical modeling of the NEA population. Considering definition of potentially hazardous asteroids (PHA), only objects with diameters more than 140 m could pose catastrophic consequences to the Earth and mankind in general. But in the same time, impacts of smaller size objects could lead to significant consequences on local level and their large predicted number increases this probability.

Due to their small size which results in faint apparent magnitude, such NEAs are discovered in a short interval of their close approach (CA) to the Earth, when their apparent magnitude are tending to be as bright as possible for a given size. This is not only facilitates the detection of such new objects but also increases their observability by small ground-based telescopes. However, apparent rate of motion during this time might exceed 10 deg d^{-1} making the observations challenging.

The used Rotating-drift-scan CCD (RDS CCD) technique allows to get images of fast-moving objects as a point, that in turn to determine the coordinates of their image centers with sufficient astrometric precision. Obtained in current research project positions show errors in the range $\pm (0.2'' - 0.3'')$ in both coordinates with comparison both to JPL's HORIZONS¹ system and NEODyS-2² service. The part of observations was obtained around time moment of minimal distance to the Earth during current CA for newly discovered NEAs. Such observations are important to extend observed orbital arc for reliable improvement of their orbit determinations and reducing orbital uncertainty, so it will be possible to recover them in next apparitions.

АНОТАЦІЯ. Сучасний стан спостережень навколоземних астероїдів (НА) показує щорічне збільшення

кількості відкриттів нових об'єктів. Однак частотний розподіл НА за розмірами показує різке зменшення кількості об'єктів з розмірами менше 300 м, що суперечить результатам теоретичних моделювань популяції НА. Виходячи із визначення потенційно небезпечних астероїдів (ПНА), лише об'єкти діаметром понад 140 м можуть мати катастрофічні наслідки для Землі та людства в цілому. Але в той же час, об'єкти менших розмірів може призвести до значних наслідків на місцевому рівні при входженні в атмосферу та зіткненні із Землею, і їх велика передбачувана кількість збільшує цю ймовірність.

Через їх невеликий розмір, що призводить до слабкої видимої зоряної величини, практично всі НА відкриваються за короткий час їх тісного зближення (ТЗ) із Землею, коли їх видима величина, як правило, стає максимально яскравою для даного розміру. Це не тільки полегшує виявлення таких нових об'єктів, але й збільшує можливості їхніх спостережень за допомогою невеликих наземних телескопів. Однак видима швидкість руху у даний період може перевищувати $10 \text{ град день}^{-1}$, що є ускладнюючим фактором для спостережень.

Використовувана методика ПЗЗ- спостережень дозволяє отримувати точкові зображення об'єктів з великою видимою швидкістю та визначити координати їх центрів зображення з достатньою астрометричною точністю. Отримані у даному дослідженні астрометричні положення НА мають похибки в діапазоні $\pm (0,2'' - 0,3'')$ для обох координат по відношенню як до ефемериди JPL HORIZONS, так і до ефемериди сервісу NEODyS-2. Частина спостережень була отримана в момент мінімальної відстані до Землі під час поточного ТЗ для нещодавно відкритих НА. Такі спостереження важливі для подовження спостережуваної дуги орбіти з ціллю надійного поліпшення визначення орбіт даних об'єктів та зменшення орбітальної невизначеності. Це дозволить провести повторні спостереження цих НА у наступних опозиціях.

Keywords: astronomical databases, observational methods, astrometry, near-Earth asteroids.

¹ <https://ssd.jpl.nasa.gov/?horizons>² <https://newton.spacedys.com/neodys/index.php?pc=1.0>

1. Introduction

The near-Earth asteroids (NEAs) are important objects for investigations of near-Earth space. The study of the orbital motion of such objects makes it possible to trace the dynamic evolution of Solar system bodies and the distribution of materials. In addition, the presence of potentially dangerous asteroids (PHA), as special group of NEAs, creates the problem of asteroid-cometary hazard and requires constant monitoring of such objects for precise determination of their orbits and the probability of collision with the Earth in the future.

The data presented on the JPL Center for NEO Studies (CNEOS) website³ shows constant growth of amount of newly discovered NEAs with 26957 objects regarding to October 2021 and more than 2200 PHAs among them. According to recent studies, current state in size–frequency distribution (SFD) give evaluations of population completeness more than 90% for objects with sizes 1+km (Tricarico, 2017; Harris & Chodas, 2021). However, the same studies suppose a significant number of small-sized NEAs and the current completeness of such populations insufficiently small despite of existed surveys denoted to NEA discovery.

It is clear that small-size NEAs have faint apparent magnitude, which makes them unobservable most of the time. These objects have short observability window during the time period of close approach (CA) to the Earth when their apparent magnitude become brighter and new objects could be discovered. Precise astrometric observations during discovery apparition allow to determine orbits with acceptable accuracy to recover objects in next apparitions. At the same time, the apparent rate of motion might exceed 10 deg d⁻¹ at significantly close distances to the Earth (Vereš et al., 2012) which makes observational process complicated. The short visibility period and high apparent rate of motion result that some of these objects remain unconfirmed (Vereš et al., 2018) or are lost due to an inappropriately precise orbit determination (Tricarico, 2017). Obviously, it requires efficient follow-up observational campaign during discovery apparition to get as much as possible precise positions and extend observed orbital arc.

The implemented Rotating-drift-scan CCD (RDS CCD) technique allows to perform reliable and effective observations of fast-moving NEAs during their CA to the Earth and calculate their positions with sufficient precision as usual celestial objects (Pomazan et al., 2021). The high apparent rate of motion is compensated by time delay integration (TDI) mode rotation of CCD in direction of object’s apparent motion, which makes possible to obtain pointed images for both the object and the reference stars (Shulga et al. 2008). The article presents results of ongoing follow-up observations of NEAs obtained as a result of a joint project to study the NEO population between Mykolaiv (Ukraine) and Shanghai observatories (China).

2. Instrumentation and observational process

It is well known that precise determination of the image center coordinates, first of all rectangular, depends on values of the signal-to-noise ratio (SNR) and full width at

half maximum (FWHM) (King, 1983). The SNR value depends on exposure time and might be improved with exposure time. But the FWHM value is determined only by the optical instrumentation design and location of the telescope, which effects to atmosphere conditions. For cases with fast-moving objects, which have high apparent rate of motion in the field of view (FOV) of telescope, the classical methods of observations causing stretching of objects images during exposure time and results in increasing FWHM and decreasing SNR. Thus, it leads to a deterioration in an accuracy when specific point spread function (PSF) is used to fit the obtained image.

The used RDS CCD technique has advantages to keep pointed images for both fast-moving target object and stars for reference if apparent object’s magnitude require longer exposure time. Therefore, it is possible to obtain higher value of SNR and small FWHM for faint objects even at the limit of the telescope’s capabilities. It yields in accurate image center determination and, consequently, calculation of precise topocentric equatorial coordinates of such objects.

2.1. Telescopes and observational technique

The two similar telescopes with implemented RDS CCD technique were used to obtain observations of NEAs: 0.5 m telescope of the Lishan Observing Station (National Time Service Center of Chinese Academy of Sciences, NTSC of CAS, China) and telescope KT-50 of Mobitel complex of the Research Institute “Mykolaiv Astronomical Observatory” (RI MAO, Ukraine) The technical details of telescopes could be seen in the Table 1. The main feature of the RDS CCD technique is usage of a rotational platform and TDI mode of CCD to obtain separate CCD frames both for reference stars and objects which have high apparent rate of motion (Tang et al., 2014; Pomazan et al., 2021) with different exposure time. Such observational technique assumes acquiring at least three frames as one set at the fixed telescope position. The further processing is to interpolate calculated plate model constants of CCD frames with reference stars to time moment of CCD frame with target object (Koziryev et al., 2010; Sybiryakova et al., 2015).

Table 1: Technical specification of the telescopes

Telescope	Lishan telescope (O85, China)	KT-50 telescope (O89, Ukraine)
Diameter and type, m	0.50 Cassegrain	0.50 Maksutov
Focal length, mm	3445	2975
FWHM, "	2.3	2.5
CCD	Alta U9000	
Size, px	3056 x 3056	
Pixel size, μm	12 x 12	
Scale, "/px	0.72	0.83
FOV, '	36.7 x 36.7	42.5 x 42.5
Filter	no	Johnson V*
* since 2018		

³ <https://cneos.jpl.nasa.gov/stats/totals.html>

2.2. Observations

The objects for observations are selected with reference to the next sources with high priority for newly discovered NEAs and objects required additional observations for confirmation of their orbits:

- the database of the International Astronomical Union (IAU) Minor Planet Center (MPC)⁴ to select fast-moving objects. The ephemerides for all listed NEAs are calculated for specified date and observational site in automatic mode with own software and objects with appropriate observability are chosen for observations;
- the services NEOScan of NEODYs-2⁵ and Scout of CNEOS⁶ of ephemeris calculations for objects from NEO Confirmation List. Because such objects usually have just a few observations they highly demand more positions to reliable orbit determination. These objects acquire maximum priority in created observational program;
- the European Space Agency (ESA) NEO Coordination Centre (NEOCC) Priority List⁷. The service classifies the need to observe objects into four categories, from urgent to low priority.

Unfortunately, the instrumental characteristics of telescopes do not allow the inclusion of target objects with an apparent magnitude fainter than 18 mag for both used telescopes.

The statistical information of NEAs observations in 2019-2021 obtained at the Lishan and KT-50 telescopes is provided in Table 2. The columns N1, N2 contain number of obtained positions and number of NEAs respectively; n1, n2 - number of positions and objects for newly discovered asteroids in the current year; (O - C) represents the mean residuals between "O" - observed positions and "C" - positions from the JPL's HORIZONS ephemeris system at the time of observations and their standard deviation values, σ .

Table 2: Observational statistics of NEAs for Lishan and KT-50 telescopes

Year	Obs. Code	N1	N2	Newly discovered	
				n1	n2
2019	O85	395	18	54	2
	O89	842	41	135	8
2020	O85	460	35	33	3
	O89	1435	35	60	7
2021*	O85	505	25	111	7
	O89	481	24	49	6

* Data regarding on October 2021

3. Astrometric results

During 2019 - 2021 observational period more than 1300 topocentric positions for 75 NEAs were obtained at Lishan telescope and more than 3200 astrometric positions for more than 100 NEAs were obtained at KT-50 telescope. Among them 12 objects from results obtained at Lishan telescope were newly discovered in considered year of observations and 21 objects for results from KT-50 telescope. The mean and standard deviation values for (O - C) differences calculated with JPL's HORIZONS ephemeris system are presented in Table 3.

As can be seen, for the newly discovered objects, there is a slight deterioration in accuracy and an increase in the absolute values of the differences (O - C) for them. It could be explained by fact that such objects usually have short observed orbital arc and not enough observations for reliable orbit determination. When the positions are added to IAU MPC database and taken into account for orbit recalculated new calculated (O - C) differences often show decreasing of absolute values (Maigurova et al., 2018).

Table 3: (O - C) differences and its errors for results obtained at Lishan (O85) and KT-50 (O89) telescopes

Year	Obs. Code	(O - C) $\pm \sigma$ (")			
		Already known		Newly discovered	
		RA	Dec	RA	Dec
2019	O85	-0.01 \pm 0.09	0.04 \pm 0.11	-0.04 \pm 0.13	0.16 \pm 0.20
	O89	0.00 \pm 0.19	0.01 \pm 0.25	0.03 \pm 0.23	-0.07 \pm 0.32
2020	O85	-0.02 \pm 0.13	-0.03 \pm 0.15	0.09 \pm 0.13	-0.12 \pm 0.16
	O89	0.00 \pm 0.22	-0.02 \pm 0.28	-0.12 \pm 0.36	0.20 \pm 0.27
2021*	O85	0.02 \pm 0.13	-0.05 \pm 0.13	-0.14 \pm 0.18	-0.01 \pm 0.17
	O89	0.03 \pm 0.25	0.03 \pm 0.30	0.07 \pm 0.30	0.13 \pm 0.41

* Data regarding on October 2021

Considering newly discovered NEAs it could be noticed that they, obviously, have high values for uncertainty parameter (U) and it correlates with apparent rate of motion. The data for selected observed newly discovered objects is presented in the Table 4.

The column **N** in the Table 4 represents number of obtained positions while column **U** contains uncertainty parameter given by IAU MPC database. Apparent rate of motion is given in the column **App. motion** with values at time moment of minimal distance to the Earth (**max.**) and during observational session at mentioned telescopes (**mean**).

⁴ <https://minorplanetcenter.net/data>

⁵ <https://newton.spacedys.com/neodyS/NEOScan/>

⁶ <https://cneos.jpl.nasa.gov/scout/#/>

⁷ <https://neo.ssa.esa.int/priority-list>

Table 4: (O - C) differences with standard deviation values for observed newly discovered NEAs

NEO	N	U	App. motion * (" min ⁻¹)		(O - C) ± σ (")	
			max.	mean	RA	Dec
K21C00O	16	6	389.9	218.5	0.37±0.15	0.28±0.13
K21C02K	29	3	19.0	11.9	-0.05±0.15	0.03±0.15
K20C01X	16	0	42.6	42.3	0.03±0.14	-0.19±0.17
K20M03X	11	4	25.2	25.2	0.02±0.05	-0.13±0.17
K20N01K	10	7	17.0	16.9	-0.02±0.05	-0.04±0.12
K21C06A	22	4	359.2	336.4	-2.03±0.25	-0.05±0.18
K21D01W	14	3	82.5	82.2	-0.14±0.10	-0.18±0.14
K21F00H	10	7	26.3	25.6	-0.01±0.13	-0.14±0.17
K21F01K	15	7	54.8	53.4	0.24±0.28	-0.24±0.29
K20Q06V	19	3	67.8	31.6	-0.01±0.13	0.37±0.17
K20R00C	10	5	41.6	36.1	-0.03±0.13	0.21±0.15
K21E05C	11	0	5.3	4.8	0.09±0.37	-0.19±0.36
K21J01G	10	5	134.2	97.9	0.13±0.14	0.17±0.17
K21N04M	10	6	102.4	102.2	0.02±0.23	0.16±0.33

4. Conclusion

The paper describes astrometric results obtained on two small-sized telescopes placed in China and Ukraine with usage of RDS CCD technique for observations. This observational technique allows to observe NEAs with high apparent rate of motion, at the minimal distances to the Earth with sufficient astrometric precision. The analysis of obtained positions with respect to JPL's HORIZONS ephemeris system shows the precision in the range 0.1" – 0.3" in both coordinates for both telescopes.

The observations of NEAs during time of their close approach to the Earth are extremely important, as their small sizes make them inaccessible to observations at another time. Obtained positions at the minimal distances to the Earth for newly discovered objects extend the observed orbital arc and are useful for improvement orbit determination so such objects could be recovered in next apparitions.

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