Multi-scale (time and mass) dynamics of space objects
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Astrometry and photometry of asteroids from the UkrVO database of astroplates

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Abstract. We present the developed methods of digitization, image processing, reduction, and scientific data mining with the latest reference catalogs, which allowed us to obtain a good positional and photometric accuracy in B-band of 6,500 asteroids down to 17.5^m from the Ukrainian Virtual Observatory database of astroplates. The archive includes FON-Kyiv, FON-Kitab, FON-Dushanbe sky surveys (1981–1996) and astroplates of the Baldone and Tautenburg observatories. For some of asteroids, observations are either completely absent or not enough over the certain time interval to the moments of their official discoveries (about 300 such objects were found). Positional observations during these time scales are highly useful for a more detailed study of the dynamics and orbital parameters of asteroids as well as the obtained photometric parameters are very complementary with present-day data for studying changes in brightness and light curves.

Keywords. methods: data analysis; techniques: image processing, photometric; asteroids

1. Introduction

The value of old photographic archives as a source of "new" scientific data does not diminish over the years. The digitizing of observational archives all over the observatories possessing the glass collections allows successful involving these data into modern-day science, including for small Solar System bodies research (Ruphy et al. (1994), Lupishko 1997, Mahabal et al. (2002); Ivezic et al. (2002); Davis et al. (2004); Goodman (2012); Pakuliak et al. (2014); DiCarlo (2018); Lehtinen et al. (2018); Villarroel et al. (2020); Vavilova et al. (2020); Khovritchev et al. (2021)). The Ukrainian Virtual Observatory (UkrVO, http://ukr-vo.org) database covers data of about 40,000 astroplates exposed in 1898–2018, from which 15,000 are digitized (Vavilova (2016); Vavilova et al. (2017)). The most of them is related to the stellar FON project (Northern Sky Photographic Survey, 1981–1996). But these images have produced a large number of faint asteroids down to 17.5^m. For some of them, observations are either completely absent or not enough over a certain time interval to the moments of their official discoveries.

Allowing to enlarge observational timescales, these data are helpful to improve the orbital elements of asteroids (Veres et al. (2015); Savanevych et al. (2015); Savanevych et al. (2015); Savanevych et al. (2018); Eggl et al. (2020)) and to validate simulations of collisions in the dynamical and kinematic studies. For example, Chernetenko

(2019) estimated the possible change in the velocity of the (596) Sheila active mass-losing asteroid. Fuentes-Munoz and Scheeres (2021) developed semi-analytical long-term propagation model of near-Earth asteroids (NEA) to calculate their close flyby probabilities. Such validation permits us to characterize the nature of objects whose orbits are potentially hazardous in the future, or which may have had a period of close passages in the past to the Earth and other planets (Farnocchia and Chodas (2021); Forgács-Dajka et al. (2021)). In this context we also note work by Pravec et al. (2012), who used albedo estimates from WISE thermal observations for revealing size dependencies of surface properties on absolute magnitude of 583 asteroids observed in 1978-2011. Solano et al. (2014) accomplished a project by the Spanish Virtual Observatory to improve the orbits of 551 NEA using old astronomical archives and 938,046 images from the SDSS DR8 to confirm or discard the presence of NEA images from previous observing epochs.

The aim of our paper is to demonstrate reliability of our approach in digitization, image processing, and reduction of the UkrVO astroplates, which allowed us to obtain a good positional and photometric accuracy in B-band of 6,500 asteroids down to 17.5^m.

2. Image processing and plate reduction scheme

All astroplates were digitized on commercial scanners Microtek and Epson with scanning mode of 1200 dpi and the gray scale of 16-bit color. The original software for image processing and further data mining was developed in LINUX MIDAS-ROMAFOT environment (Andruk (2018)). In general, the scheme of the image processing and the further reduction includes the following main steps (see, in detail, Andruk et al. (2019); Protsyuk et al. (2019); Pakuliak & Andruk (2020)):

- Conversion of files from 16-bit tiff format into 8-bit format fits, while after the preliminary tests 16-bit resolution turned out to be excessive.
- Photometric equalization of a digitized star field without applying the auxiliary flat-field images.
- Calculation of the rectangular coordinates and the photometric instrumental values for all objects registered on the astroplate.
- Separation of registered objects by exposure (case of the multiply exposed plate).
- Identification of stars of the reference catalog (Tycho-2 or GAIA DR2) by their rectangular and equatorial coordinates.
- Astrometric reduction of all objects into the reference frame at the epoch of the plate exposure with the assessment of the accuracy. The rectangular coordinates obtained for objects, corrected for systematic errors of scanners, were transformed into a system of tangential coordinates by full polynomials of 6 or 3 orders (depending on the telescope) taking into account coma and the magnitude equation.
- Photometric reduction of instrumental stellar magnitudes to a system of photoelectric standards with the assessment of the accuracy.
- Final analysis of objects to reject fictitious and erroneous images.

Of all the objects recorded on the scan, each asteroid was identified by ephemeris coordinates and magnitude at the time of observation of the JPL online service (http://ssd.jpl.nasa.gov). The diameters of the images and the maximum intensity of the central pixel of the image on the scan were also taken into account.

3. Asteroids in the FON-Kyiv sky survey

Catalog of 2292 astrometric positions and B-magnitudes of asteroids and comets with magnitudes from 16^m to 8^m (Shatokhina et al. (2019)) have been compiled from digitized photographic observations of FON-Kyiv obtained in 1985–1991. Coordinates of objects

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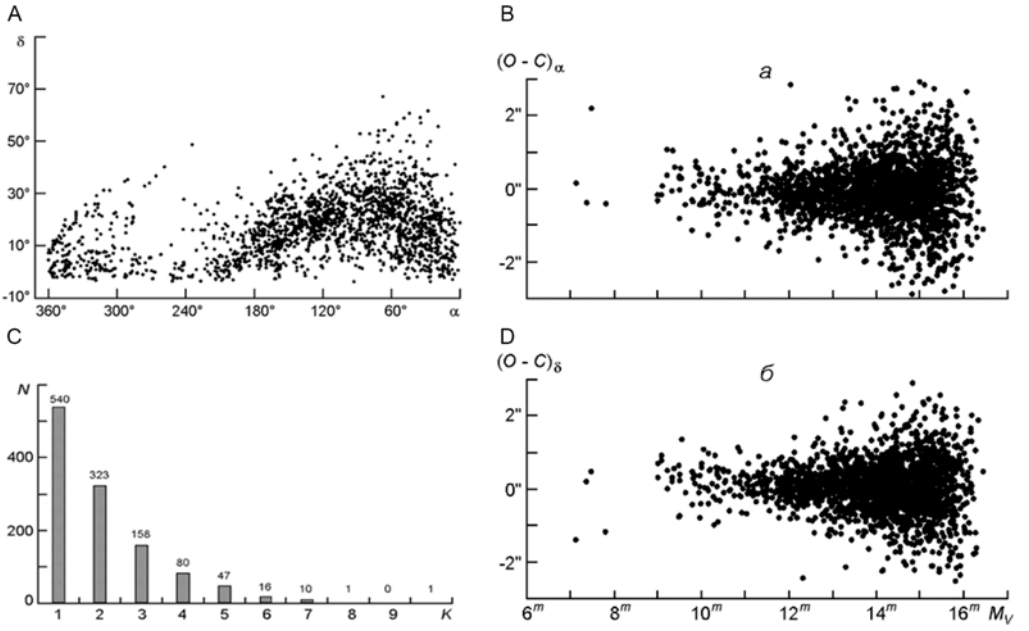

Figure 1. Parameters of array of registered asteroids from the FON-Kyiv astroplate archive.

were reduced to the Tycho-2 reference system and B-values to the system of photoelectric standards. The results of software testing and application for the determination of positions and magnitudes are given by Eglitis et al. (2016); Yizhakevych et al. (2017) and a number of related publications. Most of the registered asteroids are in the declination zone below +30 degrees. A little sample is in the high-declination zone up to +70 degrees.

Fig. 1, panel A, shows the distribution of asteroids across the celestial sphere. Fig. 1, panel B, shows the distribution of asteroids by the multiplicity of positions of each of the asteroids. All the asteroid positions were compared with JPL DE431 (http://ssd.jpl.nasa.gov/horizons) ephemeris. The obtained coordinates differences (O-C) between the observed and computed asteroid positions are given in Fig. 1, panels C and D. It was found that for 54 asteroids the observational moment precedes the moment of the asteroid discovery. Among them there are 4 asteroids with their chronologically the earliest observations in the world according the MPC data.

4. Asteroids in the FON-Kitab sky survey

FON-Kitab photographic observations were carried out in 1981–1993 with the Zeiss Double Wide Angle Astrograph (D/F = 40/300, 69”/mm) at the Kitab observatory (Uzbekistan). The application of the above described scheme (Chapter 2) resulted in a few catalogs of coordinates and B-magnitudes for more than 13 million stars and galaxies from the FON-Kitab part. Based on the FON-Kitab digitized astroplates, the catalog of 2728 topocentric positions and B-magnitudes of asteroids and comets have been compiled. Asteroid coordinates and B-magnitudes were obtained in the Tycho-2 reference catalog system and the system of photoelectric standards, respectively.

The catalog’s contents is given by Shatokhina et al. (2018). The observations were conducted with both telescope tubes, so two plates with the same center were exposed simultaneously. As a result, 1412 asteroid positions are paired, and the remaining 1316 positions are single. Based on the paired positions, the rms errors of the equatorial coordinates and B-magnitudes of asteroids were determined. Their values averaged over

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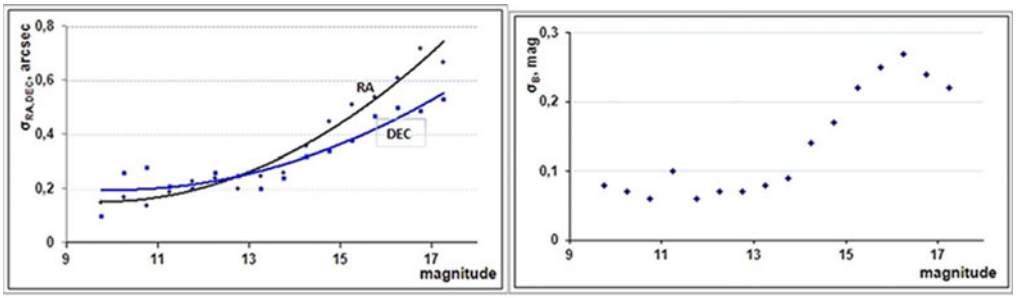

Figure 2. Positional r.m.s. errors of asteroids in FON-Kitab sky survey.

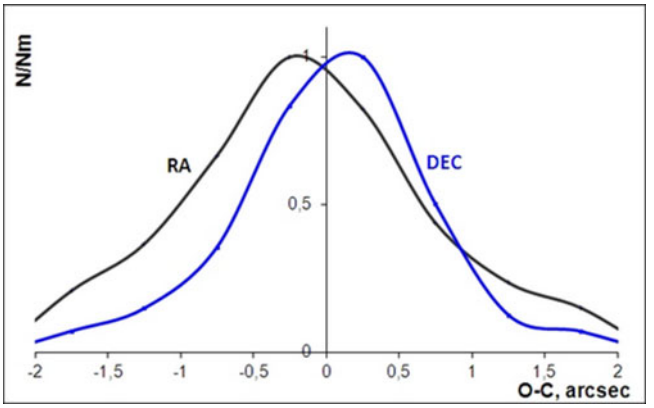

Figure 3. (O-C) differences for all asteroid positions in FON-Kitab sky survey.

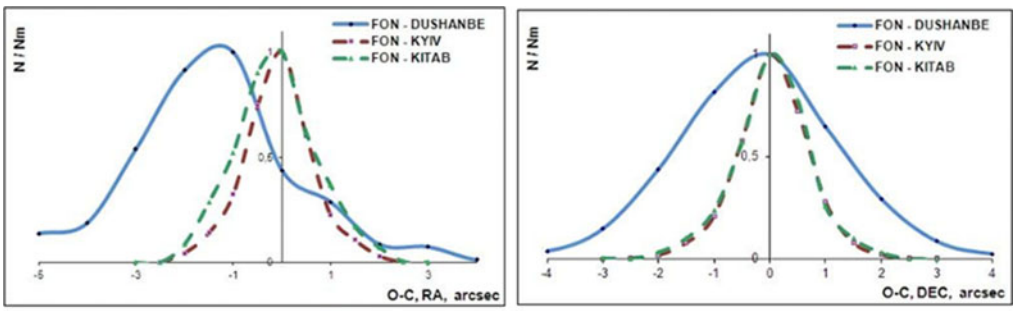

Figure 4. (O-C) differences on both coordinates for 302 asteroid positions from the FON-Dushanbe sky survey.

the magnitude intervals are given in Fig. 2. The histogram of O-C differences for all positions of the asteroids constructed from the results of comparison with the ephemeris is shown in Fig. 3. A good agreement can be noted between the results obtained from FON-Kyiv and FON-Kitab surveys.

5. Asteroids in the FON-Dushanbe sky survey

The Dushanbe part of the FON project is represented by about 1570 astro-plates obtained in 1985–1992 with a Zeiss-400 astrograph at the Hissar Astronomical Observatory of the Institute of Astrophysics of the NAS of Tajikistan (Shatokhina et al. (2020)). Image processing and plate reduction scheme (Section 2) were the same as for

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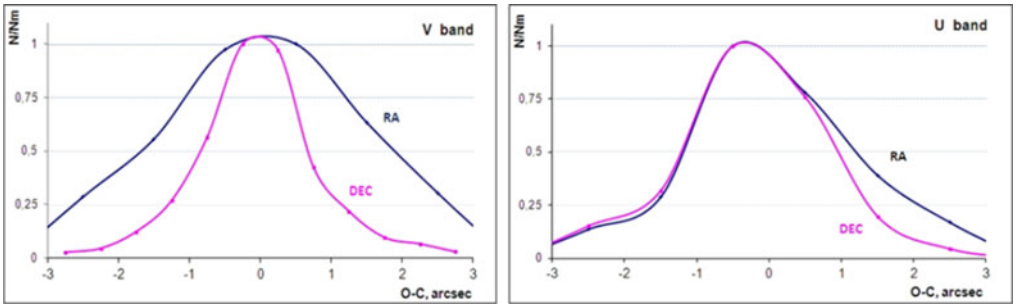

Figure 5. (O-C) differences from comparison of asteroid positions from the Baldone astroplate archive with the JPL ephemeris.

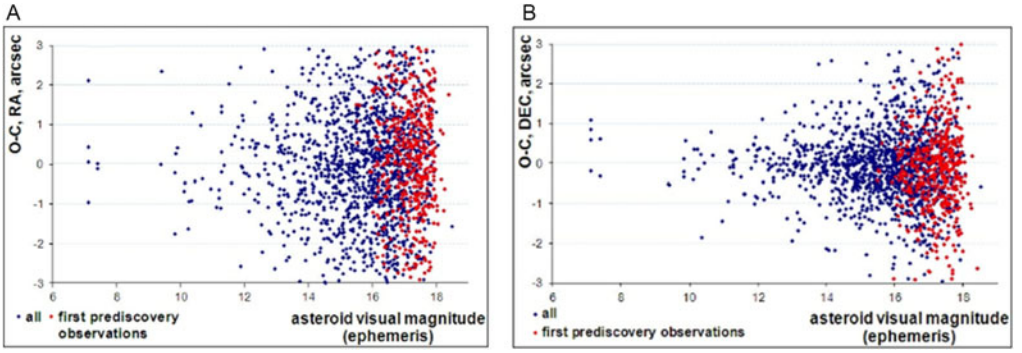

Figure 6. (O-C) differences in RA (A) and in DEC (B) for all and first prediscovery asteroid observations from the Baldone astroplate archive.

the FON-Kyiv and FON-Kitab surveys. This permits to get a star catalog with millions of objects and a preliminary list for the upcoming catalog of 300 positions of asteroids and comets with visual magnitudes from 7^m to 16.5^m.

The O-C differences in both coordinates for all asteroids are presented in Fig. 4 in comparison to similar data for FON-Kyiv and FON-Kitab. A systematic O-C shift is noticeable in the RA coordinate for all asteroid positions from the two FON-Dushanbe zones. The further analysis using data of orbital velocities of asteroids near the observational moments shows a clear correlation of the O-C with the value of their orbital velocities. The last could be the result of systematic underestimation of time in positions of asteroids. In the future, this systematic component should be clarified and excluded.

6. Asteroids in the Baldone astroplate archive

The Baldone Observatory of the Institute of Astronomy of the Latvian University owns a photographic collection of 22,633 astroplates obtained with a 1.2 m Schmidt telescope in 1966–2005. Among them there are about 780 plates in the U photometric band and 4600 film negatives in the V band, which are close to the Johnson's photometric system. In 2013–2018, the Baldone Observatory performed a digitization of these astroplates by the scheme described in Section 2. At present, 281 plates and 2167 film negatives exposed in U and V photometric ranges have been used for asteroid searching.

Based on the scan processing results, a catalog of 1848 topocentric positions and magnitudes of asteroids and comets was compiled. It includes 1678 and 170 positions and magnitudes from observations in the V and U bands, respectively, as well as 7 positions and magnitudes of comets. Astrometric and photometric reduction of digitized astroplates is performed in the Tycho-2 reference system and photoelectric standards,

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respectively (Eglitis et al. (2016), Eglitis et al. (2019). The comparison results of the asteroid positions with the JPL ephemeris (https://ssd.jpl.nasa.gov) are presented as histograms of O-C differences in Fig. 5. It was found that 490 faint asteroids have the first prediscovery observations with the Baldone Schmidt telescope. The discovery of these objects took place only 20-40 years later. Their individual location and the O-C difference compared to the other asteroid positions in the catalog are shown in Fig. 6.

Our another current project on the catalog of asteroids is based on the Karl Schwarzschild Tautenburg Observatory database by Boerngen (1991): the most asteroids are objects of main belt, 53 objects are Mars crossers, 110 double/triple asteroids, 1 NEA, 19 comets.

7. Conclusions

We presented results of processing the digitized astroplates from FON-Kyiv, FON-Kitab, FON-Dushanbe, and Baldone observatory archives allowing us to compile several positional and photometric catalogs of asteroids. Some of them could occur the earliest observations of the objects long before their official discovery. The obtained (O-C) differences evident about good accuracy, so these catalogs are highly useful for dynamical and kinematic research. All the published catalogs are displayed in VizieR as well as current databases of digitized astroplates are available through http://ukr-vo.org/digarchives/index.php?b1&1.

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