DOI:http://dx.doi.org/10.18524/1810-4215.2019.32.181732

ON THE "SOLAR SYSTEM BODIES" ASTROPLATE PROJECT OF THE UKRAINIAN VIRTUAL OBSERVATORY

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ABSTRACT. The UkrVO Joint Digital Archive of astroplates and the newest digitized data processing services allowed us to form a new approach for the creation of catalogs of astrometric and photometric characteristics of the Solar System bodies. Given this, the main goal of this approach was not only to complete the processing with the best possible accuracy of high-quality and unprocessed earlier photographic observations of the Solar System bodies but also to find new original data from these observations.

As a result, more than 6,500 new astrometric positions and stellar magnitudes of asteroids, and 3,036 positions of outer planets (Pluto, Uranus, Neptune, Saturn, Jupiter) and their satellites have been determined. Most of the positions obtained from observations of large stellar surveys of the northern sky FON (Kyiv and Kitab parts) and other surveys (MEGA, Equatorial Catalog).

The number of new obtained positions of asteroids is comparable to the total number of all positions of asteroids obtained at the Main Astronomical Observatory of the NAS of Ukraine in 1949-1996. The accuracy of new positions is higher than in traditional determinations from photographic observations, but it cannot be comparable to the accuracy of modern CCD observations.

Contrary to traditional classic definitions, digitized images of plates have produced a large number of faint asteroids down to 17.5 magnitudes, which were discovered in the early 21st century. For some of them, observations are either completely absent or not enough over the certain time interval preceding the moments of their official discoveries. These data can be obtained from photographic observations only. Based on our observations, about 300 such asteroids were found. The collection of missing data on positions over certain time intervals and their analysis can be useful not only for modern ephemeris calculations but also for studying the evolution of asteroid orbits over time.

The cooperation between UkrVO and the observatory in Baldone of the University in Latvia, astronomical and astrophysical institutes of Uzbekistan and Tajikistan make it possible to expand this work by involving numerous additional archives of digitized observations and processing services and thus obtaining new original data about the Universe.

Keywords: archives, catalog, positions, Solar System bodies

АНОТАЦІЯ. Об'єднаний цифровий архів фотографічних платівок УкрВО та новітні цифрові сервіси обробки даних дозволили сформувати новий підхід щодо створення каталогів астрометричних та фотометричних характеристик тіл Сонячної системи. З огляду на це основною метою такого підходу є не тільки завершення опрацювання якісних і необроблених раніше фотографічних спостережень тіл Сонячної системи з максимально кращою точністю, але й знаходження нових оригінальних даних з цих спостережень.

В результаті оцифрування фотоплатівок та сучасної обробки сканів було визначено понад 6500 нових астрометричних положень та зоряних величин астероїдів, 3036 положень зовнішніх планет (Плутон, Уран, Нептун, Сатурн, Юпітер) та їх супутників. Більшість з них отримані із довготривалих програм спостережень великих зоряних оглядів північного неба ФОН (Київська та Кітабська частини) та інших оглядів (МЕГА, Екваторіальний каталог).

Кількість отриманих нових положень астероїдів може бути порівняна із загальною кількістю всіх положень астероїдів, отриманих у Головній астрономічній обсерваторії НАН України у 1949-1996 роках. Точність нових положень вища, ніж точність класичних визначень координат з фотографічних спостережень, але вона не може бути порівняна з точністю сучасних ПЗЗ спостережень.

На відміну від традиційних класичних визначень, за цифровими зображеннями платівок отримано велику кількість положень слабких астероїдів до 17.5 зоряної

величини, які були відкриті на початку 21 століття. Для деяких з них спостереження зовсім відсутні або їх замало у певний часовий інтервал, попередній до їх офіційних відкриттів. Інформацію про це можна отримати тільки з фотографічних спостережень. За даними наших спостережень було знайдено біля 300 таких астероїдів. Накопичення даних про положення астероїдів у певні часові проміжки та їх аналіз може бути корисним не тільки для сучасних розрахунків ефемерид, але і для вивчення еволюції орбіт астероїдів.

Кооперація між UkrVO і Обсерваторією в Балдоне Університету в Латвії, астрономічними та астрофізичними інститутами Узбекистану і Таджикистану дають можливість розширити цю роботу, додаючи нові архіви оцифрованих спостережень і сервіси їх обробки і отримуючи, таким чином, нові оригінальні дані про Всесвіт.

Ключові слова: архіви, каталог, положення, тіла Сонячної системи

1. Introduction

The existing world databases of positional observations of the small bodies of the Solar System have a large number of photographic, modern CCD and satellite observations for these objects. Modern observations far exceed the previous ones in the accuracy of coordinates and number of positions, where new mathematical methods for the automated CCD images processing, positional frame-to-frame guidance and discovery of Solar system small bodies have a crucial role (see, for example, Savanevych et al., 2015; Savanevych et al., 2015; Savanevych et al., 2018).

However, we hope to find from digitized photographic archives those original observations that could be used in the solutions of modern kinematic and dynamic problems. By applying the methods of digitization of astronegatives developed by us, the subsequent processing of scans using the latest reference catalogs and methods, we can achieve the maximum accuracy of coordinates and magnitudes of objects. Using online Internet services, we can search, identify the necessary objects and perform a preliminary analysis of their obtained characteristics.

2. Main results

2.1. Catalogs of asteroid positions based on observations of the FON project

The results of processing of digitized plates from the Photographic Survey of the Northern Sky (the FON project) (Andruk et al., 2016; Pakuliak et al., 2016; Yuldoshev et al., 2017) contain not only the coordinates and magnitudes of stars, but also all objects that were fixed on these plates at the time of observations. They were used for a global search for small bodies of the Solar System on these plates (Golovnia et al, 2017; Kazantseva et al, 2015; Shatokhina et al, 2017; Vavilova et al, 2014). The identification is performed according to the coordinates and stellar magnitudes of asteroids, and the diameter and maximum intensity of the central pixel of the asteroid image are also taken into account. Ephemeris support of asteroids and comets at the moments of observation was made by used from the online Internet service https://ssd.jpl.nasa.gov/sbfind. After identification the corresponding equatorial coordinates and B-magnitudes of asteroids from astronegatives of Kyiv and Kitab parts of the FON project were collected in catalogs (Shatokhina et al., 2018a; Shatokhina et al., 2018b). Earlier, in cooperation with the observatory of the University of Latvia in Baldone, the catalog of 89 positions and stellar magnitudes of asteroids and comets was obtained from processing observations of clusters in the UBVR spectral bands in 1967-1996 (Eglitis et al., 2016).

We continued this work and performed the search for asteroids based on the results of processing the remaining plates observed in U, V bands. Based on the results of digital processing about 300 U-plates and more than 1460 V-films, a preliminary catalog of 1700 asteroid positions was compiled.

These catalogs contain 6958 positions of asteroids and 14 positions of comets in total (see Tabl.1). To detect ambiguous identifications, all positions of asteroids were compared with the coordinates of stars in the Gaia DR2 stellar catalog.

The quantitative and qualitative characteristics of the compiled catalogs are analyzed. Fig.1 shows the distribution of all identified asteroids by equatorial coordinates RA, Dec for all used plates from Kyiv and Kitab parts of the FON project. Most of the identified asteroids attributed to the Main Belt. Only several of them attributed to the Hilda and Mars crosser families, potentially dangerous and unnumbered ones.

Table 1: The number of identified positions of asteroids and comets in catalogs

Photographic Survey	Number of used astronegatives	Number of identified positions of asteroids \ comets	Number of asteroids that have no positions earlier 1982-1996 (or these positions are single)
FON-Kyiv (1981-1994)	2260	2282/10	4(10)
FON-Kitab (1981-1989)	1963	4589/2	~280
Baldone (1967-1996)	1760	1700/3	>40

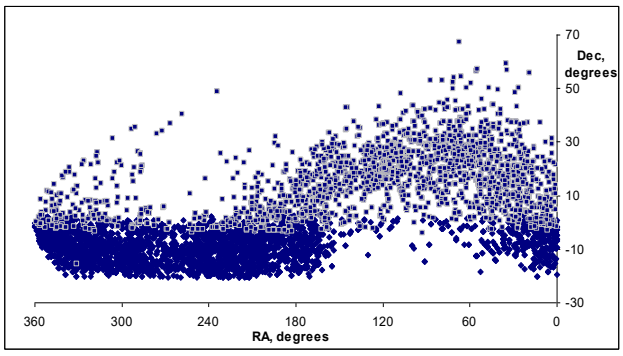

Figure 1: Distribution of coordinates RA, DEC for 4533 identified asteroids of the Kitab part (dark points) and for 2293 asteroids in the Kyiv part (light points) of the FON project.

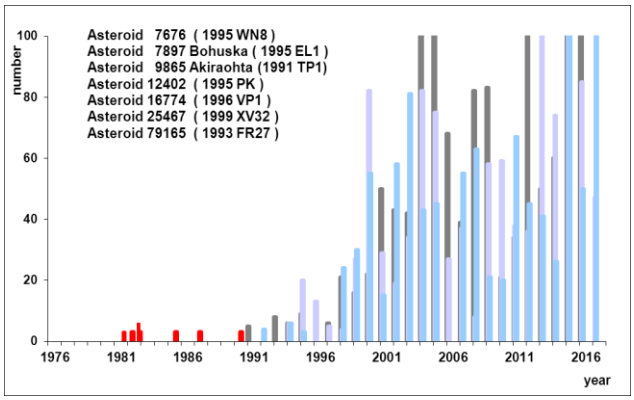

Figure 2: Time distribution of global observations of 7 asteroids according to MPC database as compared with observations of these asteroids from FON-Kyiv, FON-Kitab (red markers).

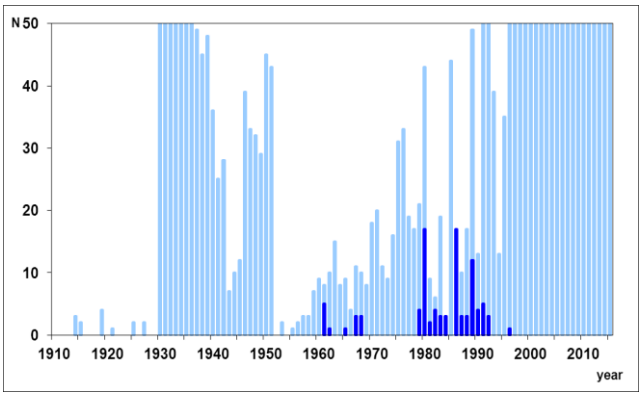

Figure 3: The number of positions of Pluto observed in the world in 1914-2015, according to the MPC data (UkrVO astroplate collection - dark blue, all - blue).

The unique fact is that we found 300 asteroids, which have the positions at that observational date only on the UkrVO astroplates. These observations of asteroids belong to those early oppositions of these asteroids which have insufficient or completely absent observational data. As an example, Fig.2 schematically shows the distribution of all known world observations of asteroids (7676), (7897), (9865), (12402), (16774), (25467) and (79165). They were discovered later and had no other observations earlier 1991. Observation of these asteroids in 1981-1991 from the FON project is shown with red markers.

Soon, we plan to continue the global search for small bodies of the Solar System based on the results of processing observations from Dushanbe part of the FON project and observations in the U, V spectral bands of the Observatory of the University of Latvia in Baldone. Using processing observations from the Dushanbe part of the FON project the first results of asteroids identification were obtained (Yizhakevych et al., 2018).

The catalog of asteroids from Kyiv part of the FON project is placed on the website of UkrVO (http://gua.db.ukr-vo.org/starcatalogs.php) and in Strasbourg astronomical Data Center (http://cdsweb.u-strasbg.fr).

2.2. Catalog of positions and B-values of Pluto

A catalog of 90 positions and magnitudes of Pluto for the period 1961-1996 was obtained from digitized photographic observations from the Joint Digital Archive of UkrVO and the Observatory of the University of Latvia. Pluto observations were made using telescopes of the Main Astronomical Observatory of the National Academy of Sciences of Ukraine (MAO NASU), Astronomical Observatory of the Taras Shevchenko National University of Kyiv, Research Institute "Mykolaiv Astronomical Observatory" (RI MAO) and Baldone Observatory of the University of Latvia.

Previously, 59 digitized astronegatives covering the period 1961-1990 were processed and obtained a catalog of astrometric positions and photometric values of the planet has been obtained (Kazantseva et al., 2015).

Both previously processed and unused astronegatives were included in the new processing. The identical type of re-scan of all astronegatives and the subsequent processing of scans were performed. Additionally, the positions of Pluto from astronegatives with multiple exposures were obtained. (Previously, only one exposure from these astronegatives was processed.) The improvement of the software for digital image processing allowed us to extract all closely located Pluto images of multiple exposures. Besides, 8 images of Pluto from the archives of observations of large photographic sky surveys of the FON, MEGA, "Equatorial catalog" were found and processed. As a result we obtained additionally 31 new positions and magnitudes of Pluto and included them in our catalog.

A comparison of all resulting positions of Pluto with the JPL PLU055 / DE431 ephemeris was performed. As a result of the comparison, mean values (O-C) for all positions were obtained, which are -0.09 and -0.15 arcsec for RA and DEC, respectively. Their standard errors are 0.58 and 0.55 arcsec.

Fig. 3 shows 90 observations of Pluto, obtained by us in 1910-2015 during the most active period of Pluto's observations in the world. Pluto's observations in 1950-1990 years are a few in the world in comparison with the observations of the periods of planet discovery and the beginning of the 21st century. Our observations were made exactly at that time. The rotation period of Pluto around the Sun is 249 years. Since the discovery and till our time only a small part of one revolution of Pluto on its orbit around the Sun covered with observations.

This catalog is placed on the website of UkrVO (http://gua.db.ukr-vo.org/starcatalogs.php) and in Strasbourg astronomical Data Center (http://cdsweb.u-strasbg.fr).

2.3. Positional catalogs of Uranus, Neptune and satellites of Jupiter, Saturn, Uranus, and Neptune based on observations at the MAO NASU and RI MAO

The glass photographic collection of UkrVO contains plates of several observational projects with images of celestial objects of different nature including external planets and their satellites. These plates were digitized using flatbed commercial Epson scanners and processed using the software developed for image processing of digitized FON photographic plates. The software has been modified to meet the requirements of the new task and takes into account the peculiarities of the observations of planets and their satellites.

Firstly, satellites of the major planets cover the wide range of stellar magnitudes and they are the dynamic objects of the Solar System. To take the photographic images

Table 2: Some statistic characteristics as the results of the processing of archive photographic observations of major planets' satellites.

Object	B, mag	n	$(o-c)_\alpha$	$(o-c)_\delta$	σ_α	σ_δ
U1 Ariel	12.1	2	-.95	.64	.43	.64
U2 Umbriel	14.4	9	-.12	.27	.63	.46
U3 Titania	13.2	33	-.09	.44	.12	.44
U4 Oberon	13.2	33	.06	.51	.17	.35
N1 Triton	13.0	9	.65	.38	.57	.46
J6 Himalia	15.2	27	.17	-.18	.36	.50
J7 Elara	15.7	7	-.10	-.09	.27	.17
J8 Pasiphae	15.9	1	.58	.08	-	-
S2 Enceladus	11.7	12	.48	.16	.68	.48
S3 Tethys	10.3	20	-.01	.10	.62	.45
S4 Dione	10.4	40	.07	.07	.44	.43
S5 Rhea	9.7	57	.15	.07	.41	.38
S6 Titan	8.3	84	.09	-.03	.35	.37
S7 Hiperion	14.2	8	-.04	.10	.01	.46
S8 Japetus	12	78	.11	.04	.41	.38
S9 Phoebe	16.4	1	.44	-.27	-	-

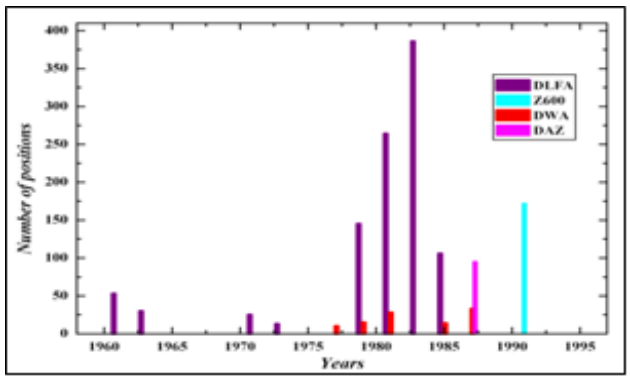

Figure 4: The distribution of observations of Saturn's satellites by year.

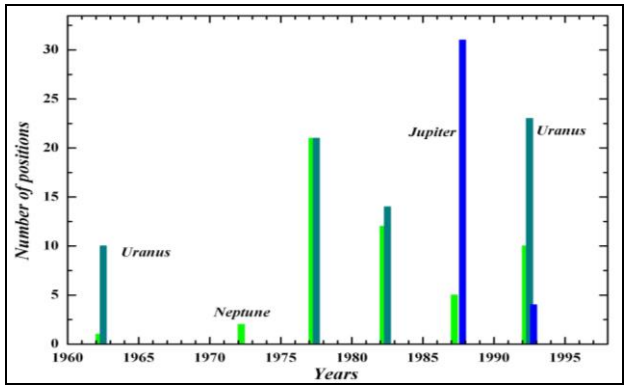

Figure 5: The distribution of observations of Uranus, Neptune, Jupiter, and their families by year.

of such faint objects like distant Jupiter's satellites, one should apply long expositions. During the exposure, the satellite can tangibly shift against stars. To hold the projection of the expected satellite image at the same point on the plate, it is necessary to compensate for the movement of the satellite by shifting the plate in the direction of its displacement (Medkof method).

Secondly, the constant movement of satellites along their orbits often causes the merger of satellite images with the image of the planet or the image of the other moon. To avoid it, every plate was exposed several times with various exposures. The split of the plate image into separate frames was made by the program algorithm.

The accuracy of the photographic plate reduction depends on telescope parameters, plate field dimensions, and a number of reference stars on the plate. The more reference stars on the plate the more accurate the connection of the rectangular coordinate system of the plain plate with the spherical star coordinate system can be established.

All observations of the satellites of the major planets in MAO NASU were conducted using four telescopes: two astrographs DLFA (D/F=400/5500) and DWA (D/F=400/2000) in Golosiiv (Kyiv, Ukraine), DAZ astrograph (D/F=4000/3000) in Kitab (Uzbekistan), and 60 cm Zeiss reflector Z600 (D= 600, Cassegrain-focus = 7500) installed on mt. Maidanak (Uzbekistan). Observations of the major planets in RI MAO was conducted using Zonal Astrograph (ZA, D/F=120/2040) telescope.

For the reduction of observations obtained with ZA, DWA and DAZ, the sixth-order polynomial was applied. The processing of DLFA plates was made using third-order polynomial. The Z600 observations were processed with a linear model. Astronegatives were digitized on the Epson commercial scanners in 1200 dpi mode. Tycho-2 catalogue was used as reference one. The internal accuracy of observations on the four telescopes DLFA, Z600, ZA and DAZ is almost the same and lies within the limits ±0.08 - ±0.19 arcsec. The accuracy of the reduction for DWA telescope is lower and is approximately equal ±0.17 - ±0.24 arcsec along both coordinates. Differences in accuracy have accordance to focal length of telescopes and pixel scale of plate images. All observations have accuracy near 0.1 pixel (Protsyuk et al., 2014).

Tabl.2 demonstrates the coherence of determined positions of satellites and their theoretic values. Columns 4 and 5 of the Table contain the mean values (O-C) for every satellite obtained as the result of comparison of calculated positions with according ephemeris data from IMCCE (http://nsdb.imcce.fr/multisat/nssephme.htm). The last two columns contain RMS errors of these differences.

Fig. 4 and Fig. 5 give the quantitative distributions of obtained positions of Saturn's, and Jupiter's, Uranus's, and Neptune's satellites by year along the total period of their observations in MAO NASU.

The processing of 750 original plate images with observations of major planets and their moons conducted in 1961- 1994 resulted in the creation of 4 catalogs:

1) catalog of 1385 topocentric positions of eight Saturn's satellites S2-S9 (Yizhakevych et al., 2017a);

2) catalog of 750 positions of Uranus and 77 positions of its satellites U1-U4 (Protsyuk et al., 2015, 2017; Yizhakevych et al., 2016);

3) catalog of 690 positions of Neptune and 9 positions of its satellite N1Triton (Protsyuk et al., 2015, 2017; Yizhakevych et al., 2016);

4) catalog of 35 positions of distant moons of Jupiter J6-J8 (Yizhakevych et al., 2017b).

These catalogs of outer planets and their satellites are placed on the website of UkrVO and in Strasbourg astronomical Data Center.

3. Conclusion

The use of new digital technologies for processing observations made it possible to increase the total number of positions of small bodies of the Solar System by searching for images from various digitized archives of observations, as well as to increase their accuracy. To maximize the accuracy of astrometric positions and increase the number of original positions of individual asteroids, we plan to use the Gaia DR2 stellar catalog and digital archives of the UkrVO also. The new processing of digitized images of some selected minor planets using modern reference catalogs of stars, performed at the RI MAO, has led to a significant increase in position accuracy compared to previous results (Protsyuk et al., 2016).

The covering of certain time intervals with missing data on asteroid positions and their analysis can be useful not only for modern ephemeris calculations, but also for studying the evolution of asteroid orbits along time. These missing data can be obtained from the digital observational archives of UkrVO and other databases. A global search of observations of such asteroids in the databases of the UkrVO (Vavilova et al., 2012; 2016; 2017) with subsequent processing of the plates will substantially increase their number.

Acknowledgment. The work was partially supported by Ukrainian Astronomical Association.

The authors are sincerely grateful to Vavilova I. B. for her support and active participation in the discussion of the results of the work and the problem as a whole.

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