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## THE RE-PROCESSING RESULTS OF PHOTOGRAPHIC OBSERVATIONS OF ASTEROIDS WITH GAIA CATALOG AT THE MAO NAS OF UKRAINE

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**ABSTRACT.** In total, about 4,500 asteroid positions were determined from photographic observations conducted at the MAO NAS of Ukraine in 1952-1996. These are the early positions of the selected minor planets, mostly bright, the observations of which were initiated by the founders of the ORBITA observational program and were made in 1952-1986. The second later positions of asteroids obtained from digitized plates from photographic observations of the Northern Sky Survey project in 1981-1996.

Using digital plate processing technologies, 2292 asteroid positions were obtained, the images of which were fixed during observations and identified during processing. The new star catalog Gaia DR2 was used to study changes in determining the accuracy of equatorial coordinates for various faint objects on plates. For several 8 plates with images of Pluto comets and faint asteroids of particular interest due to the lack of observations in the past, new complete processing of scans of these plates was performed. The Gaia DR2 was used as a reference catalog.

The asteroid positions from early observations of 1952-1986 were determined in accordance with classical linear reduction algorithms. These are 1651 positions of minor planets determined in the PPM catalog system and obtained from observations with the Double Wide-Angle Astrograph. The remaining 591 positions were determined in the systems of old reference catalogs of stars Yale, SAO, AGK3, and obtained from observations with the Double Long-Focus Astrograph. It was for these positions that the calibration with the Gaia catalog was performed. The data on the positions of minor planets digitized from publications and additional data on their reference systems deposited in previous years at VINITI (now VINITI Database RAS) were used.

Comparison with JPL ephemeris was performed both for new determinations of asteroid coordinates with the Gaia catalog, and for past determinations obtained in systems of other reference catalogs.

**Keywords:** reference catalog, asteroids positions.

**АНОТАЦІЯ.** Загалом з результатів фотографічних спостережень, виконаних в ГАО НАНУ в 1952-1996 рр., визначено близько 4500 положень астероїдів. Це ранні положення вибраних малих планет, переважно

яскравих, спостереження яких були ініційовані засновниками програми ОРБИТА і виконані у 1952-1986 рр. Інші, більш пізні положення астероїдів отримані з оцифрованих платівок за спостереженнями Фотографічного огляду північного неба у 1981-1996 рр.

З застосуванням цифрових технологій обробки платівок отримано 2292 положень астероїдів, зображення яких були зафіксовані на фотонегативах під час спостережень і ідентифіковані під час обробки. З метою вивчення змін при визначенні точності екваторіальних координат для різних слабких об'єктів на платівках був використаний новий зоряний каталог Gaia DR2. При цьому для декількох платівок із зображеннями Плутона, комет і слабких астероїдів, що представляють особливий інтерес за відсутності спостережень у попередні часи, було здійснено нову повну обробку сканів цих платівок. При цьому Gaia каталог використано в якості опорного.

Положення астероїдів ранніх часів спостережень обчислювались відповідно до класичних лінійних алгоритмів редукції. Це 1651 положень малих планет, визначених в системі каталогу PPM і отриманих за спостереженнями на телескопі ПША. Решта 591 положень визначені в системах старих опорних каталогів зірок Yale, SAO, AGK3 і отримані на телескопі ПДА. Для їх калібрування з каталогом Gaia використано оцифровані з публікацій дані про положення малих планет, а також додаткові дані щодо відповідних опорних систем, депоновані у попередні роки в ВІНІТІ (нині ВІНІТІ РАН).

Порівняння з ефемеридами JPL проведено як для нових визначень координат астероїдів з каталогом Gaia, так і для минулих визначень, отриманих в системах інших опорних каталогів.

**Ключові слова:** опорний каталог, положення астероїдів.

### 1. Introduction

Old astrometric observations are still in use in the astronomical research and collected in different databases. Observations made on a long interval of time are necessary to model the evolution of these objects and dynamical

study of Solar System objects. The recent availability of the Gaia Data Release 2 allows us to make a new reduction of old data and to get observations of the past with today's accuracy. Old observations have been reduced using reference star catalogs accurate from 100 up to 1000 mas. Besides, these catalogs were built with different reference frames. The Gaia reference star catalog can provide star positions accurate to one mas at the beginning of the XX-th century, allowing us to make a new and precise astrometric reduction of old observations. Moreover, these old observations will be reduced in the same reference frame than current ones. In the same way, photometric calibrations based on catalogs dating back by several decades, had a very low accuracy by modern standards. The Gaia photometric data will allow a new photometric reduction of old photographic plates.

To increase the accuracy of the coordinates of asteroids, comets, planets, and their satellites, we used the new star catalog Gaia DR2 for a new reduction of old photographic observations.

The influence of the various catalog reference system on the positions of asteroids obtained from photographic observations has been studied previously (Maigurova et al., 2017; Major et al., 1996; Protsyuk et al., 2016). According to these results the new processing of digitized images of some selected minor planets using modern reference catalogs of stars has led to a significant increase in positional accuracy compared to previous results.

## 2. Results

In total, about 4,500 asteroid positions were determined from photographic observations conducted at the MAO NAS of Ukraine in 1952-1996. These are the early positions of the selected minor planets, mostly bright, the observations of which were initiated by the founders of the ORBITA observational program and were made in 1949-1996 (Golovnya et al., 2001; Major et al., 1984; Onegina et al., 1970; Vasilenko et al., 1979). The second later positions of asteroids obtained from digitized photographic observations of the Northern Sky Survey project in 1981-1996 (Shatokhina et al., 2018).

Fig. 1 shows the time distribution for all positions of asteroids obtained from photographic observations at the MAO NASU. All early observations were made using two telescopes: the Double Long-Focus Astrograph (DLFA, 400/5500) in 1952-1986 and the Double Wide-Angle Astrograph (DWA, 400/2000) in 1976-1996. As a result of processing these observations using classical linear reduction algorithms, the positions of selected minor planets were determined. Various reference catalogs of stars were used.

591 positions of selected minor planets from observations on DLFA were determined in reference systems of catalogs Yale, SAO, AGK3. And 1651 positions of these planets from observations on DWA were determined in the PPM catalog system.

On the contrary, the later 2292 positions of asteroids obtained from the digitized observations of the FON project in 1981-1996 were determined using the modern Tycho-2 reference catalog of stars and non-linear algorithms for reduction calculations.

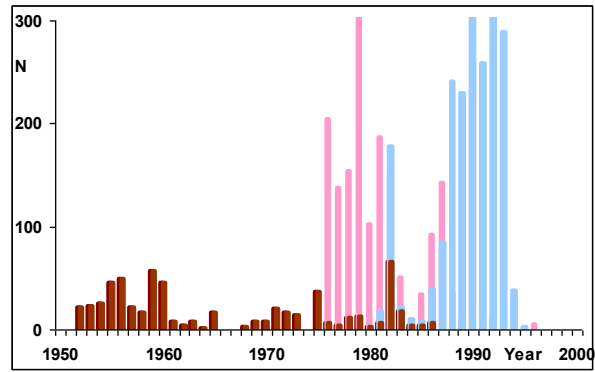


Figure 1: The distribution on time for all positions of asteroids received from photographic observations at the MAO NASU with DLFA and DWA (including FON observations).

Therefore, we examined two approaches to the re-processing of old observations using the Gaia catalog: 1) for digitized photographic plates of the FON project; 2) for non-digitized and previously processed oldest photographic observations in 1952-1986. The first results from that processing were presented.

### 2.1 New full processing of digitized images of plates with Gaia DR2 catalog

The first approach was a new full reprocessing of scans accumulated in the Joint Digital Archive of the Ukrainian Virtual Observatory. The Gaia catalog was used as a reference for obtaining optimal solutions in reduction algorithms. From the collection of observations of the FON project, plates with images of faint asteroids (7676) and (25467) of the particular interest for us were selected. In addition, 2 plates with images of comet 65P and 3 plates with images of Pluto were selected too. Their scans were obtained previously with the Epson commercial scanner with 1200 dpi resolution. The previous processing results of these scans with the Tycho-2 reference catalog were available too. Additionally, the scan of each plate was processed three times with the reference catalog of Gaia. Reference stars in each case were limited in magnitude to the 13<sup>m</sup>, 14<sup>m</sup>, and 17<sup>m</sup>. As a model of coordinate reduction was a sixth-order polynomial.

As an example, for plate 56, the standard errors  $\sigma$  of determining the coordinates of stars for 4 independent processing options shown in Table 1. When the total number of reference stars on the plate was increased by faint stars up to 17 magnitudes, the mean square errors in determining the coordinates of the stars increased by more than 3 times compared to similar other processing options of this plate.

Table 1: The comparison results of scan processing with Tycho-2 and Gaia catalogs for plate GUA040C000056A

Pl=56, Reference catalog	N reference stars	$\sigma_{RA}$ ,	$\sigma_{Dec}$ ,	$\sigma_B$ ,
		arc sec	arc sec	mag
stars				
Tycho-2	1198	.13	.10	.11
Gaia 13-m	1958	.27	.25	.12
Gaia 14-m	3615	.14	.13	.11
Gaia 17-m	11301	.50	.49	.12

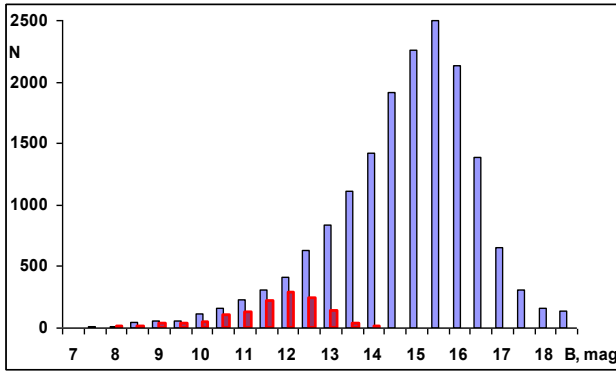


Figure 2: Distribution of 17 552 identified stars from Gaia DR2 (blue bars) and 1320 from Tycho-2 (rose bars) along B magnitudes on the plate № 56.

The coordinates of 17,552 stars from 7 to 18 magnitude obtained from plate processing were identified with the corresponding coordinates of the stars of the Gaia catalog (Fig. 2). For comparison, the same figure shows the number of stars identified with the stars of the Tycho-2 catalog.

Stars with absent proper motions and stellar magnitudes of the Gaia catalog were excluded from further analysis, as well as visually binary and triple stars. For the remaining 16,031 stars, individual differences O-C on both coordinates were formed, where the "O" values are the coordinates of the stars obtained from the plate, and the "C" values are their corresponding coordinates from the Gaia catalog at the observational moment. The mean O-C values and their root-mean-square (RMS) errors on both coordinates for B magnitudes intervals were determined and shown in Fig.3 (a,b,c,d).

In processing with Gaia 17-m the smallest mean O-C values (Fig.3a, Fig.3b) for all stars in each magnitudes interval were obtained. Besides, these values are most stable over the entire range of stellar magnitudes. In other processing options, mean O-C values differ systematically and randomly from the previous one. The trend line of the mean O-C difference values is especially pronounced in the RA coordinate.

Fig.3c, Fig.3d shows the RMS errors of the O-C values. Only processing from Gaia 17-m leads to the smallest and constant values of RMS errors of O-C on a wide range of magnitudes from 9 to 14. The results from processing from Gaia 14-m are the closest to similar results from Gaia 17-m. A large increase in RMS errors for all processing options is observed for stars fainter than 14-15 magnitudes.

Table 2: The O-C values for asteroids identified on plate 56 and processed with Tycho-2 and Gaia 17-m catalogs.

Asteroid	Mv	Tycho-2		Gaia	
		(O-C), RA, arcsec	(O-C), Dec, arcsec	(O-C), RA, arcsec	(O-C), Dec, arcsec
6	9.87	.61	.36	-.08	.31
87	12.49	-.61	.45	-.50	.76
414	14.76	-.20	-.35	.23	.00
521	13.10	.04	1.08	-.39	1.40
567	13.31	-.59	.44	.30	.31
859	14.83	.05	1.05	-.07	.77
3754	14.53	-1.19	.15	-2.27	.52
6325	15.72	-3.24	.06	-3.16	.45
7676	15.84	-3.20	2.16	-3.02	2.57

In addition to studying the accuracy of determining the coordinates of stars for different stellar magnitudes intervals, we compared the coordinates of asteroids identified on this plate for four plate processing options. To determine the O-C of asteroids, comets and Pluto we used ephemeris from JPL NASA (<https://ssd.jpl.nasa.gov/?horizons>). The results for nine asteroids identified on plate 56 and processed with Tycho-2 and Gaia 17-m catalogs presented in Table 2. The O-C values have changed but remained still large for faint asteroids with asteroid's apparent visual magnitudes  $M_v$  equal to 15<sup>m</sup>.

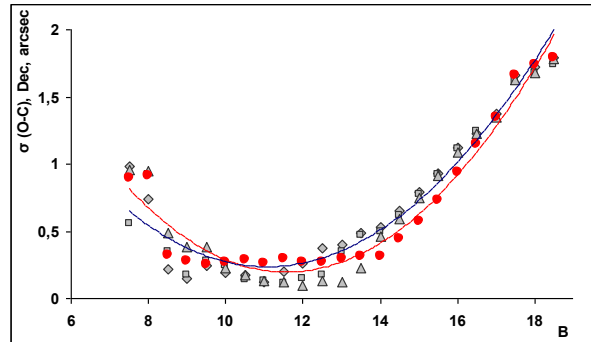
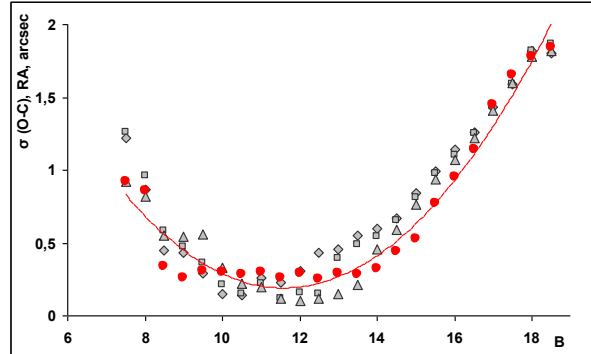
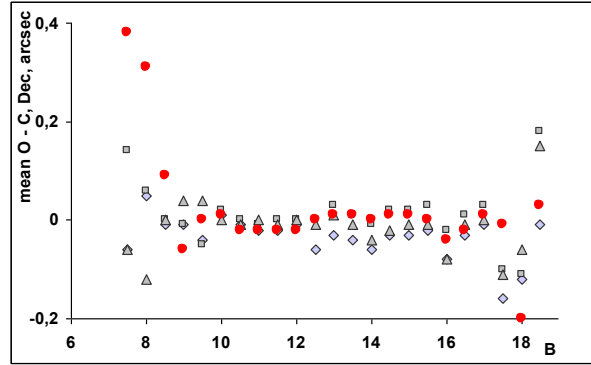
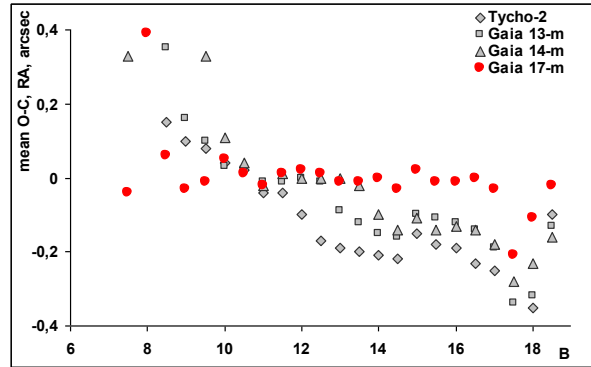


Figure 3(a,b,c,d): Mean O-C coordinate differences for 16,031 stars and their RMS errors in RA, Dec plotted against B magnitudes intervals for four processing options: Tycho-2, Gaia 13-m, Gaia 14-m, Gaia 17-m.

## 2.2 Processing of non-digitized oldest photographic observations in 1952-1986 with the Gaia catalog

For the earliest observations of minor planets, plate measurements and the results of their processing were not preserved. But, in addition to the positions of minor planets, detailed information about the reference catalog, reference stars for reduction calculations, their coordinates and dependences has been preserved. The publication of such additional data on the positions of selected minor planets was envisaged by the founders of the ORBITA observational program for their repeated reprocessing with other reference catalogs. But without the availability of these data in digital formats and the use of online Internet services to search for stars in catalogs in Strasbourg astronomical Data Center (<http://cdsweb.u-strasbg.fr>), this work did not seem real. Now it can be done quickly and easily.

Therefore, to re-process such observations with the Gaia catalog, we decided to use another approach. It was as follows. New positions of minor planets were obtained by adding the corresponding coordinate differences of the reference stars in two reference catalogs, weighted by the values of the dependencies. Note that earlier such observations of minor planets were processed using linear methods of reduction calculations. Therefore, our approach to calibrating the positions with the Gaia catalog data is identical to the new complete re-processing of these observations.

Comparison with JPL ephemeris was performed both for new determinations of asteroid coordinates with the Gaia catalog, and for past determinations obtained in reference systems of other catalogs.

Fig. 4 shows the comparison results for 60 positions of Ceres and 57 positions of Pallas. For each from them, the O-C calculated in reference systems of Gaia, Tycho-2 and other catalogs (Yale, SAO, AGK3). Differences of the type “original catalog minus Gaia” and “Tycho-2 catalog minus Gaia” were formed for each of the two O-C values calculated from the positions of the asteroid in two reference catalog systems.

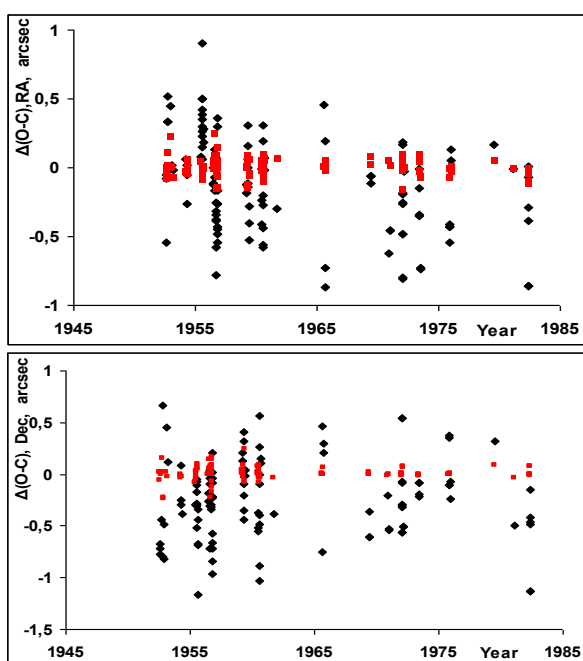


Figure 4: Individual differences between the two O-C values for each two asteroid positions that were determined in two catalog systems: Original catalog and Gaia (black markers) or Tycho-2 and Gaia (red markers) (top – on coordinate RA, below – on coordinate Dec).

The values of O-C for the asteroid positions in the Gaia catalog system are almost identical to the similar values in the Tycho-2 catalog system. But at the same time, these values differ significantly from the O-C in the systems of the previous original catalogs Yale, SAO, AGK3.

## 3. Conclusion

The main idea was to find ways to improve the accuracy of coordinates for faint asteroids of  $14^m$ – $16^m$  and for observations of small bodies of the solar system with epoch differences of more than 50 years and processed using various reference catalogs of stars. And as an additional result, a complete catalog of all the positions of asteroids from photographic observations at MAO NASU was compiled.

According to the re-processing of digitized images of several plates with the Gaia DR2 catalog, the most optimal solution was processing with the inclusion of all stars up to 17 magnitudes in the reference system. The systematic component of the error in determining the coordinates has become minimal and stable over a wide range of stellar magnitudes. For faint objects, the random component of the coordinate error is still large and amounts to about 1 arc second. A possible reason for this may be, first of all, insufficient exposure of the plates to reliably determine the coordinates of faint objects.

According to published data, a catalog of 591 positions of selected minor planets obtained from observations with the DLFA telescope in 1952-1986 was collected. It is part of a complete catalog of all asteroid positions obtained from photographic observations at the MAO NASU.

Experience in calibrating the positions of the bright selected minor planets in the Gaia and Tycho-2 catalog systems showed that no significant differences in the coordinates of the asteroids were found. But compared with the old reference catalogs Yale, SAO, AGK3, the differences in the coordinates of the asteroids are great both in the random and in the systematic component. It should be noted that the reference stars on each plate were bright stars from only 8 to 11 magnitudes, which could have an effect on the conclusion obtained.

It is necessary to conduct additional studies on different observational material about the influence of the use of the Gaia catalog as a reference on the coordinates of celestial objects.

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