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EFFECT OF THE REFERENCE CATALOG SYSTEM ON THE ASTEROID POSITIONS IN THE MPC DATABASE

The results of analysis of the selected MPC asteroid positions are presented. Systematic errors in star positions arising from the use of different reference catalogs and astrometric weighting problems have been discussed using observations of the 12 selected asteroids. The observational series for these asteroids include 30-year period and are obtained using Mykolaiv Zone Astrograph during 1960—1990. The residuals $(O—C)_{RA,Dec}$ of the selected asteroids have been analyzed.

Keywords: asteroids, optical position observations, reference catalogs, astronomical database.

Modern ground-based observations can provide the accuracy of asteroid positions better than 0.1" on both spherical coordinates. However, a number of tasks, such as the estimation of asteroid masses by dynamic method, the detection of Yarkovsky effect, the problem of correlation of dynamic and kinematic coordinate systems and others require sufficiently long time series of observations, which makes it necessary to use various astronomical databases. The most comprehensive source of data on the position of small bodies of the solar system is archives of the Minor Planet Center (MPC) [1].

As of 09.01.2016 the MPC database contained 145,416,300 asteroid positions. One of the components of bias error in the case of combining observations separated in time is the use of different reference catalogs for calculating asteroid positions. The modern format of data presentation in MPC provides information about the reference catalog used for astrometric reductions, but for the old observations the retrieval of this information is often difficult. As of 09.01.2016, the MPC list included 48 reference catalogs. The list of codes of catalogs, information on which is encrypted as letter in the MPC line of data is available at: http://www.minorplanetcenter.net/iau/info/CatalogueCodes.html. Since 1998, more than 90% of observations sent to MPC contain information about catalogs, while for the period of 1960—1990 this information is available only for 10%. These observations constitute a relatively small percentage of the total, but they are very important to study the slowly evolving effects. Fig. 1 shows a comparison of the overall distribution of the observations (in logarithmic scale) in the MPC database and the observations containing information about the catalogs for 1800—2016.

STATISTICS OF THE USE OF CATALOGS

As noted above, the observation data in the database are assigned to 48 catalogs used at different times as reference ones for calculating the asteroid positions. These catalogs have a different frequency of use. Table 1 shows the frequency of use of catalogs as a reference one when performing astrometric reductions for MPC observation database for 1800—2016.

As one can see from Table, catalog PPM (Position and Proper Motion, 1988) was the most com-

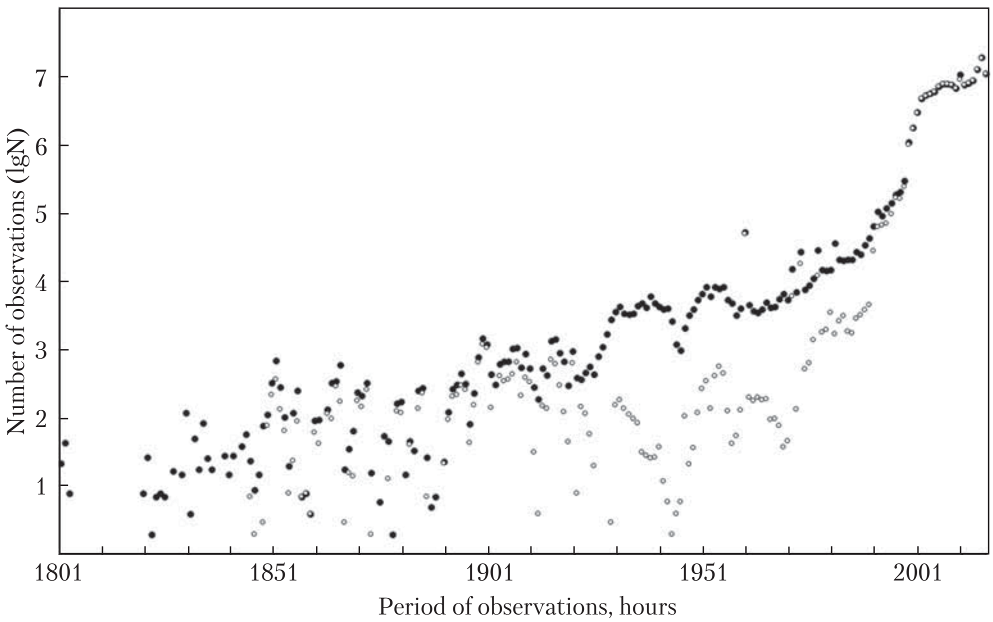

Fig. 1. Distribution of number of observations of MPC database for 1800–2016 (dark dots – all observations, light dots – observations for which information on reference catalog is available)

mon reference catalog for the reductions over several decades [2]. Therefore, analysis and correct account of its systematic errors are of great importance for using the photographic observations of 19th—20th centuries. Starting with the 1990s, CCD observations have been widely used in astronomy, which leads to a significant increase in the intrinsic accuracy. However, small fields of view of the CCD frame don't enable the direct use of high-precision cosmic *Hipparcos* and *Tycho* catalogs as reference ones when calculating the asteroid positions. Therefore, the asteroid positions in the MPC database for the period of 1990—2010 are obtained with different reference catalogs in HSRF system, including various versions of the USNO catalog. At the end of 20th — beginning of 21st centuries, the most widely used catalogs were USNO A2.0 [3] and USNO B1.0 [4]. Later, these catalogs were found to have quite significant errors in the declination system [5]. In addition, the USNO A2.0 catalog

Table 1

Statistical Data on the Use of Reference Catalogs for Calculating the Asteroid Positions in MPC Database for 1800–2016 (based on [1])

Observation period	*N*	*N*1	*N*2	Mostly often used catalog
1800—1850	1197	306	1	PPM
1851—1900	10356	7009	3	PPM, GSC-ACT, UCAC4
1901—1950	103376	7911	11	PPM, UCAC2
1951—2000	7703297	6792018	35	USNO A1.0, S1.0, A2.0, GSC
2001—2016	137598000	135137700	25	USNO A2.0, B1.0, UCAC2-4, 2mass, URAT1

Note: *N* is total number of observations in the MPC database for the period, *N*1 is number of observations containing information about the reference catalog, *N*2 is total amount of used reference catalogs in the specified period; the last column shows the most frequently used reference catalogs.

does not have its proper motions, while the accuracy of USNO B1.0 catalog proper motions is extremely low. These facts could significantly affect the calculated values of asteroid positions based on them. The appearance of UCAC catalogs (1—4) has significantly improved the situation with reference catalogs for the processing of small fields.

However, it should be noted that 12 years elapsed between the appearance of UCAC1 that covered only the Southern hemisphere and all-sky catalog UCAC4. In addition, between the different versions of these catalogs there are also systematic differences that deteriorate the accuracy of asteroid positions. Unfortunately, for various reasons, not all observers follow the MPC recommendation to use UCAC4 [6] for astrometric reductions, so the number of reference catalogs remains large.

EFFECT OF REFERENCE CATALOG ON ASTEROID POSITIONS

The residual differences (*O–C*) are often used to assess the accuracy of positional observations of Solar system bodies. Here, *O* is asteroid positions obtained from observations in the system of selected reference catalog; *C* is the value calculated based on the modern dynamic model. Analysis of observations [7] has showed that the average residuals (*O—C*) have statistically significant deviations from zero, mainly because of systematic errors of star catalogs used for the reduction of observations. This conclusion has been further developed in [8]. The authors of [8] have obtained systematic differences for the 6 most common catalogs: USNOA1.0 [9], USNO-A2.0, USNO-B1.0, UCAC2 [10] and Tycho2 [11] with respect to the 2MASS catalog [12] used as reference one for the processing of observations of Pan-STARRS PS1 project (Panoramic Survey Telescope and Rapid Response System).

Two years later, it was found that the Pan-STARRS PS1 data had coordinate-dependent systematic differences with ephemeris of (0.05–0.1)" [13] despite a high accuracy of the observations. It was a result of lack of proper motions in the 2MASS catalog. The authors of [14] proposed to

Table 2

Average Residuals $(O-C)_{\mathrm{RA,Dec}}$ and Their Standard Deviations for Selected Reference Catalogs

Reference catalog	Number		Period	(*O—C*) ± *SD* (1), mas		(*O—C*) ± *SD* (2), mas	
	N	%		RA	Dec	RA	Dec
m GSC-ACT	4470	22	1961—2016	−25 ± 456	−2 ± 456	−15 ± 501	28 ± 514
g Tycho2	3560	18	1997—2015	5 ± 93	−4 ± 108	5 ± 93*	−4 ± 108*
r UCAC2	2668	13	2002—2016	−71 ± 525	−209 ± 591	−66 ± 527	−206 ± 591
r UCAC2 **	2111		2005—2013	−56 ± 375	−30 ± 373	−65 ± 385	−28 ± 374
p PPM	1876	9	1976—2002	−38 ± 383	5 ± 326	−40 ± 479	90 ± 438
c USNO-A2.0	1360	7	1995—2016	−160 ± 915	−56 ± 1006	−309 ± 958	−339 ± 1026
l ACT	1218	6	1997—2008	−24 ± 193	−5 ± 170	−24 ± 193*	−5 ± 170*
u UCAC3	1164	6	1960—2016	−88 ± 347	97 ± 375	−99 ± 454	181 ± 468
u UCAC3 **	1134		2011—2013	−90 ± 307	131 ± 301	−100 ± 426	218 ± 402
C SAO	1085	5	1961—1998	−168 ± 942	58 ± 900	−168 ± 942	58 ± 900
o USNO-B1.0	1024	5	2001—2016	25 ± 389	−55 ± 464	7 ± 450	−240 ± 486
q UCAC4	734	4	2012—2016	22 ± 601	−256 ± 783	2 ± 601	−268 ± 788
q UCAC4 **	533		2013—2016	−14 ± 417	25 ± 565	−30 ± 424	16 ± 571

Note: * The catalog data are not adjusted using the approached proposed in [14]; ** Without the observation data of observatory 703.

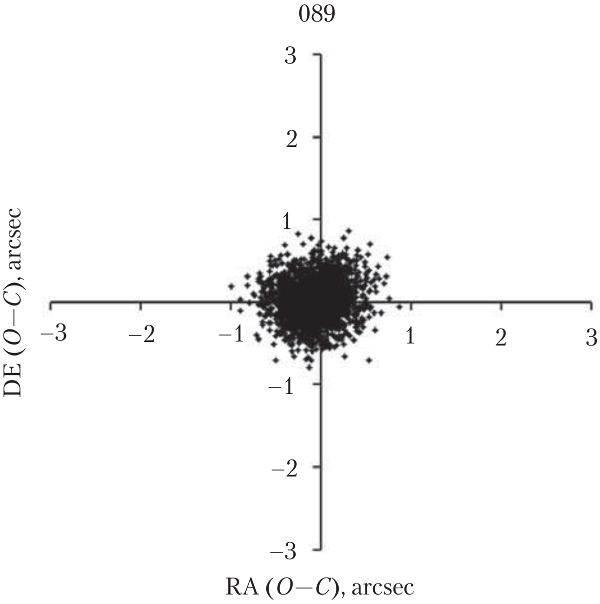

Fig. 2. Cross distribution of residuals $(O{-}C)_{RA,Dec}$ for observations of observatory 089 (Nikolaev (Mykolaiv) Observatory)

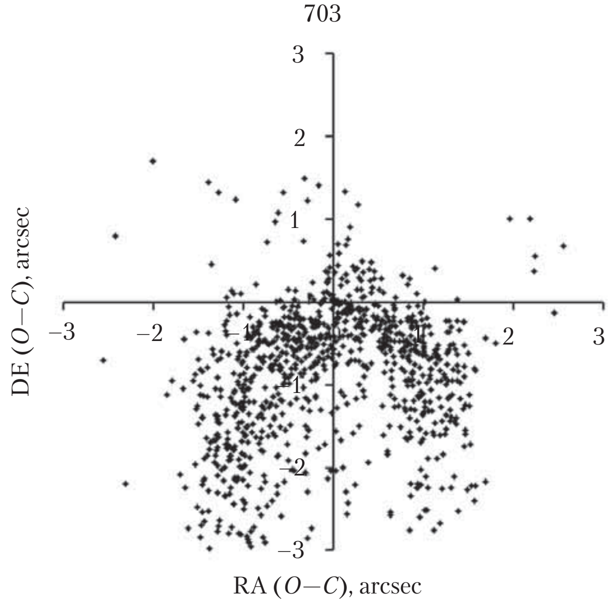

Fig. 3. Cross distribution of residuals $(O{-}C)_{RA,Dec}$ for observations of observatory 703 (Catalina Sky Survey)

complete the catalog 2MASS with proper motions from PPMXL [15] and obtained systematic differences for 19 of the most common catalogs of MPC database with respect to the proposed version of the reference catalog. Table with these differences is available at: ftp://ssd.jpl.nasa.gov/pub/ssd/debias_2014.tgz. It can be used to convert long series of asteroid observations into the system of uniform reference catalog that is a combination of 2MASS star positions with proper motions from PPMXL [15]. The systematic differences for the epoch of observation of each position are given in AstDys-2 [16]. Open Internet resource AstDys-2 provides dynamic information about asteroids, including the elements of their orbits and the residual differences with ephemeris. The service uses asteroid positions from the MPC database and enables quick quality assessment of observations sent to the MPC by different groups of observers.

Twelve asteroids from the program of observations of selected minor planets to determine the link parameters between the dynamic and the catalog coordinate systems were selected. These asteroids were observed at RI «MAO» over 30 years. For each of the 12 asteroids all positions with the differences $(O{-}C)$ and the values of catalog bias according to procedure proposed in [14] were taken from the AstDys-2 database. The observations that did not contain information about reference catalog and for which $(O{-}C)$ values exceeded 3", at least, for one coordinate, were excluded from the array of differences. The final array contains 20 703 positions of 12 asteroids observed in the period 1960—2016 that makes up only 30% of the total number of positions. Further, the array of $(O{-}C)$ differences was divided based on reference catalog and observatory code. Totally, 23 reference catalogs have been used, with over 90% of positions for each asteroid in the array obtained using only 10 reference catalogs. Table 2 shows the average residuals for right ascension (RA) and declination (Dec) and their standard deviations (SD).

Table contains two options of $(O{-}C)_{RA,Dec}$. For the option (1) the original position from the MPC database was used while for (2) the asteroid positions are corrected for the systematic difference between the reference catalogs according to the

Table 3

Average Residuals $(O-C)_{Ra,Dec}$ and Their Standard Deviations for Selected Observatories

Observatory code	Number of observations		Period	Reference catalogs	$(O-C) \pm SD$ (1), mas	
	N	%			RA	Dec
689 Flagstaff	4449	22	1994—2014	g, l, z, a	−4 ± 104	−3 ± 120
089 Nikolaev	2509	12	1961—2014	m, r, q	−55 ± 240	29 ± 231
084 Pulkovo	1772	9	1959—2007	u, r, m, o	−67 ± 304	94 ± 269
083 Golosseevo	1127	6	1976—1996	p	−37 ± 405	−43 ± 333
975 Valencia	1061	5	1985—1993	C, m	−49 ± 975	−72 ± 951
983 San Fernando	979	5	1978—1989	m, p	−65 ± 996	−53 ± 969
703 Catalina	929	5	1999—2016	r, q, d, u	−70 ± 876	−847 ± 814
673 Wrightwood	796	4	1998—2016	r, l, g, q	7 ± 86	4 ± 75
006 Barcelona	736	4	1988—2002	p, m	−16 ± 374	44 ± 293
H07 Cloudcroft	295	1	2005—2008	m, c	−55 ± 368	71 ± 316
699 LONEOS	271	1	1998—2008	o, w, c, a	−28 ± 400	74 ± 924

approach [14]. The letter before the catalog names in Table 2 corresponds to their designation in the MPC database. These data show that the catalog bias adjustments for given array of selected positions does not lead to the desired result. No significant differences between the mean residuals are obtained. Possible reasons for this may be errors in the PPMXL proper motions system [15] and possible erroneous cross-identification between catalogs with different star density when catalog bias differences were calculated. However, the main reason, apparently, is a significant part of low accurate observations with systematic errors included in the data studied. This situation requires the assignment of a system of weights for solving tasks that use large amounts of positions obtained with various accuracy. Partition of the studied positional array by the basis of observatory code flag showed that it contained observation data of 233 observatories. However, 76% of all positions accounted for 10 observatories. The share of all others does not exceed 1%. Table 3 shows the average differences $(O-C)_{RA,\ Dec}$ and their standard deviations for these 10 observatories. As one can see from Table 3, the most accuracy of observations for observatories ranges within 0.2—0.4".

The analysis of cross distributions of residuals has showed that, except for the observations of observatory 703, these distributions are symmetrical, which means that the errors are random and there is no correlation between the errors for right ascension and declination. As an example, the mutual distribution of residual differences for the observatories 089 (Nikolaev Observatory) and 703 (Catalina Sky Survey) are presented in Fig. 2 and Fig. 3. As can be seen from the Figures, the distribution of residual differences for the observations of the 703 observatory is non-random in nature and requires further investigation. These observation data cannot be used for solving the tasks requiring high position accuracy. Exclusion of observation data of this observatory from Table 3 has materially changed mean residuals and their standard deviations for the positions obtained in the system of reference catalogs UCAC2 and UCAC4.

CONCLUSIONS

The errors of asteroid positions are the main factor limiting the accuracy of determination of their orbits. Today, the accuracy of modern CCD observations is less than 0.1". This level of accuracy requires to take into consideration the systematic differences related to the use of different reference catalogs for processing of asteroid observations. To obtain heterogeneous series of data covering turns of orbit it is necessary to transform the asteroid positions into the system of uniform catalog realized ICRF system in optical range. In the author's opinion, a single reference catalog proposed in [14] has several shortcomings as a result of, primarily, insufficiently accurate PPMXL proper motions system.

Obtaining of heterogeneous observation data series for time periods of 30 years and longer is complicated by the fact that random error of individual observations can significantly exceed the error component related to the use of different catalogs. Usually, this problem is solved by introducing various systems of weights and criteria of outlier of individual observations. The statistical methods for correction of observations having large systematic errors can only partially solve the problem of obtaining heterogeneous series of data for several orbit passes. So, digitization and remeasurements of photographic plates dated 1950—1990 in the system of modern accurate astrometric catalogs can improve the situation significantly.

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ВПЛИВ СИСТЕМИ ОПОРНИХ КАТАЛОГІВ НА ПОЛОЖЕННЯ АСТЕРОЇДІВ У БАЗІ ДАНИХ MPC

Наведені результати аналізу положень вибраних астероїдів з бази даних MPC. На прикладі рядів спостережень 12-и обраних астероїдів досліджуються систематичні похибки в положеннях об'єктів, що виникають через використання різних опорних каталогів, і проблема призначення вагових коефіцієнтів окремим спостереженням. Масиви положень обраних астероїдів також включають 30-річний період спостережень цих об'єктів, отриманий на Миколаївському зонному астрографі в 1960—1990 рр. Виконано аналіз залишкових різниць $(O-C)_{\rm RA,Dec}$ обраних астероїдів.

Ключові слова: астероїди, позиційні оптичні спостереження, опорні каталоги, астрономічні бази даних.

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ВЛИЯНИЕ СИСТЕМЫ ОПОРНЫХ КАТАЛОГОВ НА ПОЛОЖЕНИЯ АСТЕРОИДОВ В БАЗЕ ДАННЫХ MPC

Приведены результаты анализа положений избранных астероидов из базы данных MPC. На примере рядов наблюдений 12-и избранных астероидов исследуются систематические ошибки в положениях объектов, возникающие из-за использования различных опорных каталогов, и проблема назначения весов отдельным наблюдениям. Массивы положений избранных астероидов также включают 30-летний период наблюдений этих объектов, полученный на Николаевском зонном астрографе в 1960–1990 гг. Выполнен анализ остаточных разностей $(O-C)_{\rm RA,Dec}$ избранных астероидов.

Ключевые слова: астероиды, позиционные оптические наблюдения, опорные каталоги, астрономические базы данных.