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MODERN CCD OBSERVATIONS OF SELECTED MINOR PLANETS FOR THE CONNECTION OF DYNAMIC AND KINEMATIC COORDINATE SYSTEMS

A. Pomazan, N. Maigurova

Research Institute "Mykolaiv Astronomical Observatory",
Observatorna 1, 54030, Mykolaiv, Ukraine, *antpomaz@gmail.com*

ABSTRACT. One of the methods of determining the orientation parameters of the dynamic and kinematic coordinate systems is to use of long-term series of ground-based observations of selected asteroids. For achievement of the best accuracy of the link parameters the high precision and uniformly covering the asteroids orbit observations are necessary. The analysis of the available observations of selected asteroids was made with usage MPC database. The value of the true anomaly at the moment of observation was selected as parameter of orbit covering. It is shown that there are orbital segments without precise observations. This was taken into account when forming the observational list for the telescope KT-50 (Mobitel complex). 1596 positions of 50 asteroid have been obtained during 2014-2016. The comparison of the calculated positions with ephemeris obtained by on-line service HORIZONS was made. The RMS errors of the differences (O-C) were about 0.1 arcsec for both coordinates. The comparison of the obtained results with observations of the some ground based observatories and Hipparcos satellite shows high accuracy and uniformity of Nikolaev asteroid observations.

Keywords: astrometry, CCD observations, asteroids

1. Introduction

The International Celestial Reference System (ICRS) was adopted by International Astronomical Union (IAU) as new reference system in 1997. The space catalogs Hip-parcos and Tycho were chosen as practical sky realization of this system in optical and near-infrared bands (HCRF). 48 asteroids have included in final list of objects to be ob-served by ESA satellite Hipparcos. They were regularly observed during 37 month of missions. 2282 astrometric positions of 48 asteroids reduced in parallel with the stars in the Hipparcos reference system. The one of scientific objective for these observations was obtaining of the link between dynamic and kinematic reference frames (Hestroffer, 1995). However, the results of determination of the link parameter using only these observations were not successful for some reason (Bougeard, 1995, 1997). The orientation of the dynamical ephemerides with an error less than several tenths of mas was determined by the complete set of VLBI observations of spacecrafts (Pitjeva, 2011). It should be noted, that small period of these observations allow to get only orientation angles. It is need to have long series of observations for obtaining the rates of change of these parameters. In addition, CCD observations, which have widespread use in optical astronomy since 1990, could not be processed directly with Hipparcos catalog due to small fields of view. There were more than 30 catalogs are used as reference for astrometric reductions of asteroids. But each of these HCRF realizations has its own errors in stars positions and proper motions and the orientation of the catalog reference frames itself can also have errors. The dynamical system that are determined by the theories of motion of major planets and asteroids either didn't take in account the effect of all known asteroids due to the lack of certainty data on their masses.

Therefore, determining the mutual-orientation parameters of these frames and the rates of their changes still remains an important modern problem.

2. Program of observations

Currently the Minor Planet Center (MPC, (http://www.minorplanetcenter.org/iau/mpc.html) contains the most full asteroid position database that can be used for study of mutual orientation of dynamic and kinematic systems. The problem of connection of the dynamic and kinematic coordinate system needs the right choice of the asteroid list. The observational programs of these asteroids have been discussed since last century (Numerov, 1936; Batrakov, 1990, 1999). The main selection criterion is the availability of high-precision long series of observations with a uniform filling of a few turns of the orbit.

The KT-50 observational program is combined on the base of the next overlapping lists:

a) list of 48 asteroids that have been included in Hipparcos program. There are 2282 positions in MPC with code 248 (Hipparcos);

b) list of 343 asteroids, whose masses are included in parameters of JPL dynamical model of motion;

c) list of 15 selected minor planet, that was adopted by IAU for observations to determine the orientation of the stellar reference frame relative to the dynamical one. Photographic observations of “h”-level accuracy of 12 asteroids from this list have been made at Nikolaev Zonal astrograph during more than 30 years.

There were selected 308 asteroids taking into account the visibility conditions and the characteristics of the KT-50 telescope. For all of these asteroids the samples with positions were chosen from MPC database. The majority of these asteroids have a long history (of over 100 years) of observations. It should be noted, that positional accuracy is very different depending on epoch of observations, place of observation, completeness of astrometric reduction etc. The evaluation of the accuracy of individual observatories in one period was obtained with usage of the file residuals.txt available at MPC web-site (http://www.minorplanetcenter.net/iau/special/residuals.txt) . The analysis of the uniformity of the distribution of observations along the arc of the orbit was performed for all asteroid positions in samples and only for positions for which the value of root mean square error (RMS) of the (O–C) differences in residuals.txt file does not exceed 0.3″.

As a parameter which indicates the uniformity of filling orbit by observations was selected the value of true anomaly. True anomaly at epoch defines the position of the orbiting body along the ellipse at a specific time (the "epoch"). The values of true anomaly were calculated with on-line service HORIZONS of Jet Propulsion Laboratory (http://ssd.jpl.nasa.gov/horizons.cgi).

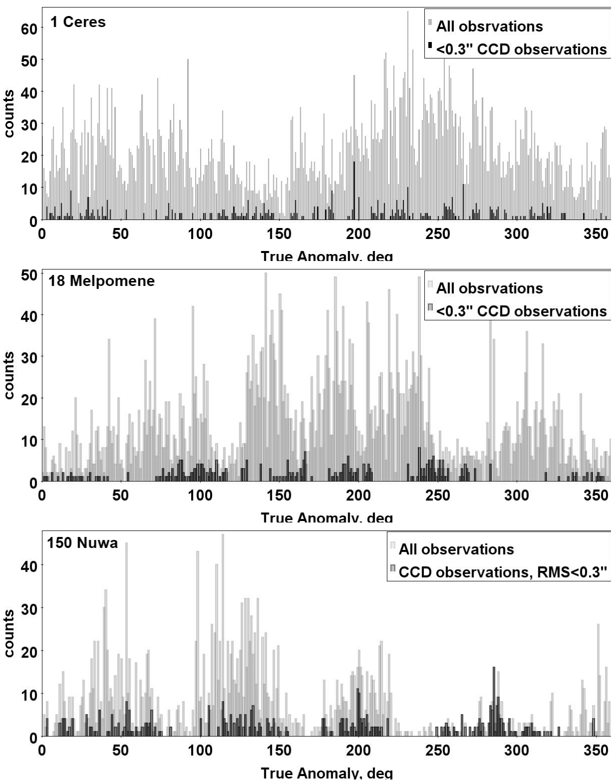

Figure 1: The distribution of the true anomaly value for a) (1) Ceres, b) (18) Melpomene, c) (150) Nuwa. Grey color correspond all MPC positions, black – only selected positions for which mean annual RMS of (O–C) differences less than 0.3″.

The histograms of true anomaly distributions for (1) Ceres, (18) Melpomene and (150) Nuwa asteroids are presented in Figure 1 as an example. It is easy to notice, there are segments of the orbit not filled with observations, especially in the histogram corresponding high-precision observations. These so-called “windows” are take in account for creation of observational program. It should be note, the majority of high-precision positions relate to CCD-observation obtained after 1990 year, so Figure 1 shows necessity to continue accurate optical observations of the asteroids from foregoing lists.

3. Observations and Reductions

The observations of selected asteroids were carried out at telescope KT-50 (Mobitel complex) of Nikolaev Astronomical Observatory (observatory code 089). The telescope KT-50 (D=0.5 m, F=3.0 m) has begun regular observations of selected asteroids and NEO objects since 2011 (Ivantsov, 2012). The CCD camera Alta U9000 (3056x3056 pix, 12x12 mkm^2) of Apogee Imaging Systems allows us to get frames with 42.0'x42.0' field of view with 0.83″/pix of scale. The observations were carried out in time delay and integration mode with time of exposure 60-85 seconds using R filter close to R photometric band of Johnson-Cousins-Bessel system. The astrometric reductions of observations were made using Astrometrica (http://www.astrometrica.at) software. Model of linkage of 4th order polynomial between measured and tangential CCD coordinates was chosen. The UCAC4 catalog was used as reference catalog for processing of all data.

1596 positions for 50 selected asteroids were measured from the observations during 2014-2016 at the telescope KT-50. The equatorial coordinates of the asteroids at the epoch of observation were obtained as result of standard astrometric reductions. We have used the catalogue UCAC4 as the reference astrometric catalog for reduction.

We have made the comparison of observed positions (O) with the calculated ephemeris (C) provided by on-line service HORIZONS and have calculated the residuals (O−C) in both coordinates. Since the observational time for a series of frames for one object usually did not exceed 20-40 min, the object position in the series of frames obtained during one night were calculated with a constant set of reference stars and practically in one point of the orbit. These circumstances exclude the systematic component of error connected with the reference catalog and the orbital motion and allow us to use the mean RMS of the (O–C) differences for one series of observations as an evaluation of the internal accuracy of our measurements. The mean internal accuracy of a single position is 0.061″ in right ascension and 0.055″ in declination for the selected asteroids in range of 10.5-15.5^m. It's a little better than normal mean accuracy because the selected objects are bright enough, which made it possible to obtain the asteroid images with high signal to noise ratio. The obtained results of (O–C) differences in right ascension and declination and their RMS for some asteroids with long series of observations are given in Table 1.

To estimate external accuracy of our observations and to compare our results with other observatories open database AstDys-2 (http://hamilton.dm.unipi.it/astdys/) was

Table 1. Differences (O−C) and their RMS for the asteroids with long observation series.

Asteroid name	Number of images/series	Time period		RA		Dec		mag
		begin	end	O−C, ″	σ_α, ″	O−C, ″	σ_δ, ″	
113 Amalthea	114/8	05-07-2015	26-09-2015	0.039	0.059	-0.001	0.054	11.59-12.58
*129 Antigone	29/2	18-03-2014	21-03-2014	0.078	0.027	0.024	0.03	11.81-11.83
334 Chicago	149/11	02-07-2014	30-10-2015	0.031	0.059	0.033	0.052	13.2-14.1
*349 Dembowska	18/2	18-03-2014	21-03-2014	0.009	0.044	0.002	0.023	10.6-10.74
*451 Patientia	15/1	21-03-2014		-0.065	0.046	0.015	0.041	11.84
*704 Interamnia	30/2	18-03-2014	21-03-2014	0.081	0.042	-0.033	0.032	11.77-11.87
714 Ulula	247/4	03-08-2014	31-09-2014	0.020	0.048	0.079	0.036	13.74-14.08
778 Theobalda	80/6	02-08-2014	30-10-2014	0.019	0.058	0.004	0.047	14.45-15.18
1171 Rusthawelia	60/4	12-08-2014	30-10-2014	-0.006	0.044	0.061	0.041	13.61-14.33
909 Ulla	59/4	01-04-2014	26-07-2015	0.034	0.063	0.088	0.048	13.63-14.71
Average					**0.049**		**0.040**	

* The asteroids are from list of observational program of Hipparcos space mission.

Table 2. Differences (O−C) and their RMS for the samples selected by observatory code.

Observatory code	Number of asteroids	Number of observations	Time period		RA		Dec	
			begin	end	O−C, ″	ε_α, ″	O−C, ″	ε_δ, ″
*089 Nikolaev	50	1596	03-2014	4-2016	0.023	0.090	0.048	0.101
248 Hipparcos	48	5096	11-1989	03-1993	-0.071	0.114	-0.000	0.073
673 Table Mountain Observatory	48	3812	05-1997	07-2016	-0.004	0.074	0.003	0.059
689 U.S. Naval Observatory, Flagstaff	48	18304	10-1994	05-2014	-0.006	0.082	-0.002	0.089
999 Bordeaux-Floirac	17	202	04-1997	08-2005	-0.034	0.068	-0.005	0.098

* Data were calculated over all observed asteroids for 2014-2015 at KT-50 telescope of Mobitel complex RI NAO.

used. AstDys-2 contains dynamical information for asteroids from MPC database including differences (O–C) for each position. The samples of records corresponding to observations of the Hipparcos program asteroids were chosen from AstDys-2 for the some good in astrometric sense observatories. Only CCD observations are taking in account for calculations. The observations of the all program asteroids obtained during 2014-2016 years were used for Nikolaev observatory table data. The statistical comparison results are given in Table 2. The mean values of the (O−C) differences and their RMS were calculated with usage 3-sigma criteria. The number of outliers is not exceeds 3% of the total samples.

It can be seen that external accuracy of the modern ground-based CCD observations not worse than Hipparcos accuracy was. The mean values of the external accuracy for Nikolaev observations are 0.09″ and 0.10″ in right ascension and declination, respectively. This value is comparable with the precision of the best ground-based positions definitions.

Conclusions

The program of asteroid observations to determine the orientation parameters of the dynamic and kinematic coordinate systems was formed. It takes into account the uniformity of the distribution of already available observations along the orbit arc.

The database of 1596 accurate topocentric positions for 50 asteroids was obtained. Mean precision about 0.1″ in both coordinates were achieved.

The comparison of the obtained observations with observations of space mission Hipparcos and some ground-based astronomical observatories was made. The results have been shown the high level of accuracy of the KT-50 Nikolaev observations that is comparable to Hipparcos level of accuracy and the other ground-based observatories.

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