The astrometric observations of planetary satellites, close approaches and occultations of stars by asteroids and mutual events in the systems of planetary satellites with the 26-inch refractor of Pulkovo observatory in 1995 - 2006 ⋆

T.P.Kiseleva, I.S.Izmailov, A.A.Kiselev, E.V.Khrutskaya, M.Yu. Khovritchev

Central Astronomical Observatory of RAS, Russia, 196140, Saint-Petersburg, Pulkovskoye chaussee 65/1

Abstract

An astrometric and photometric observations of major planets, their satellites and asteroids have been made with the 26-inch refractor of the Pulkovo observatory during the period from 1995 to 2006. The CCD (ST6) and photographic observations were carried out. Accurate relative position of of satellites of Jupiter and Saturn have been derived. The positions of Saturn have been calculated using the theoretically predicted coordinates of satellites relative to the planet without measurements of the photographic images of the planet. Also the observations of Hale-Bopp comet and Mercury transit have been made. The 26-inch refractor has been included into the international campaign PHEMU-2003: photometric CCD observations of mutual occultations and eclipses of Galilean Satellites. The light curves of the events have been obtained and parameters of the events have been determined.

Key words:
Astrometric and photometric CCD observations, planetary satellites, occulatations of stars by asteroids
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1. Introduction

The traditional programs of astrometric researches of Solar System bodies at the Pulkovo observatory began at the end of XIX century (Kiseleva T.P., Khrutskaya E.V., 2006). Only photographic observations of major planets and their satellites had been carried out before 1995. Both the CCD (as a main method) and photographic observations have been made since 1995. Series of accurate relative positions and equatorial coordinates of planetary satellites have been obtained as a result of these observations. The current and future researches programs include astrometric and photometric observations of:
– the main satellites of Jupiter and Saturn;
– mutual events in the systems of satellites of Jupiter, Saturn and Uranus (in 2007-2008);
– close approaches of asteroids to the Hipparcos and Tycho-2 stars and occultations of stars by asteroids;
– selected comets and other interesting events (such as Mercury transit).

2. The observations of planetary satellites

The 26-inch refractor of Pulkovo Observatory (F/D = 650/10413 mm) have been equipped with the CCD camera ST6 with the following parameters: full frame format is 242×375 pixels, pixel size is $23\times27\,\mu m(0.46\times0.53\,arcsecs)$, field size is $170\times129\,arcsecs$. During the period from 1995 to 2005 the satellites of Jupiter and Saturn were accessible for the observations at Pulkovo observatory. The CCD field of view allows to obtain the images of two or three satellites per frame. The photographic observations of satellites with large field of view has supplemented the CCD observations. The accuracy of relative positions of the satellites is less than 0.1 arcsec.

The "scale-trail" method was applied for astrometric reduction of photographic observations (A.A. Kiselev, 1989). The relative coordinates ("satellite minus satellite" or "satellite minus planet") have been determined. This method is effective in the case of small field of view of the 26-inch refractor because it does not require presence

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Email address: melon@gao.spb.ru (T.P.Kiseleva, I.S.Izmailov, A.A.Kiselev, E.V.Khrutskaya, M.Yu. Khovritchev).

of reference stars with precise coordinates. The images of satellites diurnal trails were used to determine the orientation of measured distances between satellites.

The CCD positions of the satellites were calculated by taking into account the influence of bright planet aureole (Izmailov I.S. et al., 1998).

Series CCD observations include 10 to 100 CCD frames. Each satellite position was determined as an average within a separate series. At first the reduction of CCD-field was made by the "scale-trail" method. The accuracy of CCD positions of the satellites was limited due to small size of the CCD field of view and therefore a short trail length (Kiseleva T.P., 2004). A new technique of CCD-field reduction was applied to solve such problem. This technique requires a parallel observation of satellites and the reference stars of TYCHO-2 (Kiseleva T.P., Izmailov I.S. et al., 2004). In this way the internal accuracy of relative coordinates of the satellites was improved to 0.02 to 0.05 arcsecs.

The coordinates of Saturn have been derived from the observations of its satellites without measurements the images of the planet. The method allows to exclude the systematic phase errors and other errors of the measurements of planetary disks. The set of Saturn positions (45 positions in the period from 1994 to 2004) was obtained with the accuracy about 0.11 arcsec that was derived from comparison of Saturn positions with the DE405 theory (Kiseleva T.P., Kalinichenko O.A., Mozhaev M.A., 2004).

As a result of systematic astrometric observations of planetary satellites in the period from 1995 to 2006 several hundreds of positions of Galilean and eight main Saturnian satellites and the Saturn positions have been obtained. The observational data were compared with modern theories of satellites motion (IMCCE: V.Lainey, v.1.1; TASS 1.7) (A. Vienne, L.Duriez, 1995). The internal accuracy of relative positions is within 0.01 to 0.10 arcsecs and for the external errors are within 0.10 to 0.20 arcsecs.

The data of CCD and photographic observations have been published in the Pulkovo observatory astrometric databases (www.puldb.ru).

3. The observations of close approaches and occultations of stars by asteroids

Eight occultations and close approaches of asteroids to stars have been observed with 26-inch Refractor during the period from 1998 to 2001. The series of CCD observations were carried out during the event about. The distances between the star and asteroid as a function of time were determined with a high precision. Also minimum distances with the standard error about 0.01 arcsecs, moment of the closest approaches or the moment of an occultation with the standard error about 0.4 second, relative velocities of asteroids, equatorial coordinates of asteroids and (O-C) have been determined. These parameters of events are seen in Table 1.

The variations of relative magnitude during the approach the asteroid (454) Mathesis to the star GSC 4960196 have been detected. The estimated period of rotation of asteroids is 4 hours (Kiseleva T.P., Izmailov I.S., Mozhaev M.A., 2002).

4. The observations of mutual events in the system of Galilean satellites in 2003

CCD photometric and astrometric observations of mutual events in the systems of Galilean and Saturnian Satellites were carried out at Pulkovo observatory with the 26-inch refractor in 1995 (PHESAT 1995), in 1997 and in 2003 (PHEMU 1997 and PHEMU 2003) (N.V.Emelianov, et al., 2000) and (Izmailov I.S., Khovritchev M.Yu. et al., 2003). Twenty photometric observations of ten occultations and ten eclipses have been done in 2003. 100 to 1000 CCD frames were obtained for each event. The exposure time for each frame was about 0.1 s. The combination of yellow and blue filters with the effective wavelength of 550 nm was used. The results of photometric and astrometric observations are presented in Table 2 and Table 3.

The minimum distances, their moments and relative satellite velocities for all occultations were determined. The standard errors of minimal distances are within 0.01 to 0.02 arcsec.

An improved procedure was used in processing of astrometric observations of occultations. It allows to determine the parameters of events in the cases when photometric observations were not successful.

5. Other observations of Solar system objects with 26-inch refractor

The photographic observations of Hale-Bopp comet were obtained with the 26-inch refractor during the period from March to April 1998. The main goal of these observations was determination of the accurate coordinates of the comet. As a result of astrometric observations the thirty six positions of comet have been obtained with the accuracy about 0.35 arcsec. The comparison of observational data with the Ephemerides had been done at ITA RAS (The Institute for Theoretical Astronomy of Russian Academy of Sciences) (Kiseleva T.P., Kiselev A.A., et al., 1998). The displacement of comet photocenter has been revealed. The value of displacement from the nucleus in direction from the Sun is 1.2 arcsec.

A clearly spiral structure and hemispherical envelopes inside the comet head were seen in obtained images. They were observed in various distances from the nucleus and changed their shape with time. Several important physical parameters of the Hale-Bopp comet have been derived from the analysis of these structures and comparisons of our results with those of other authors. The angular distances of the envelopes from the nucleus of the comet, their velocities, the masses and sizes of dust grains and the time scale of the comet nuclear activity and some other param-

Table 1
The results of observations of approaches and occultations.

Ast.	t_0 (UTC) (h, m, s)	r_0 arcsec	ΔX_0 ΔY_0 arcsec	V_x V_y $arcsec/h$	α_p (h, m, s) δ_p(deg, $arcmins$, $arcsecs$)	$(O-C)_\alpha$ (s) $(O-C)_\delta$ ($arcsec$)
39	19 03 05.8 ± 1.2	0.702 ± 0.012	+0.223 ± 0.011	+30.090 ± 0.014	06 06 40.503	+0.012
			−0.665 ± 0.012	+10.069 ± 0.015	+15 32 31.096	+0.026
535	17 47 37.2 ± 18.2	48.419 ± 0.013	+34.015 ± 0.010	−3.991 ± 0.002	09 07 55.724	+0.044
			−34.458 ± 0.050	−3.994 ± 0.003	+25 37 00.219	−0.210
454	21 43 41.6 ± 1.8	1.163 ± 0.004	−0.160 ± 0.018	+34.759 ± 0.009	13 01 43.424	+0.025
			−1.152 ± 0.007	−4.835 ± 0.005	−03 58 39.424	−1.160
11	22 47 09.9 ± 3.2	27.185 ± 0.010	+10.199 ± 0.006	−22.040 ± 0.011	09 35 40.602	+0.002
			+25.200 ± 0.011	+8.920 ± 0.018	+17 35 06.472	+0.333
97	23 34 10.1 ± 0.4	20.410 ± 0.003	+13.039 ± 0.002	−27.099 ± 0.003	13 00 09.582	+0.028
			+15.702 ± 0.004	+22.504 ± 0.007	+02 23 18.460	−0.169
40	20 47 31.7 ± 15.2	60.599 ± 0.009	+30.151 ± 0.008	+16.777 ± 0.024	09 31 46.174	+0.021
			+52.566 ± 0.009	−9.623 ± 0.026	+20 01 13.330	+1.022
111	00 37 50.4 ± 02.3	0.027 ± 0.014	+0.005 ± 0.018	−27.343 ± 0.026	00 32 31.307	−0.032
			−0.027 ± 0.014	−5.550 ± 0.021	+10 29 11.750	−0.110
64	19 07 40.2 ± 01.3	0.143 ± 0.011	+0.016 ± 0.016	+43.682 ± 0.033	06 45 25.673	−0.044
			+0.143 ± 0.010	−4.864 ± 0.022	+23 07 25.033	−0.297

Table 2
Results of CCD photometric observations of mutual events in the system of Galilean Satellites in 2003.

Data and event 2003	T_0 (UTC) h m s	σ_{T_0} s	T_1 h m s	T_2 h m s	Δmag	$\sigma_{\Delta mag}$
0106 2E1	23 32 50.879	00.657	23 25 30.815	23 40 10.942	0.676	0.022
0203 4O1	17 12 12.794	00.676	17 09 27.472	17 14 58.116	0.597	0.023
0203 2O3	23 31 08.646	01.452	23 24 43.976	23 37 33.316	0.288	0.009
0203 2E3	23 39 41.208	01.112	23 32 06.039	23 47 16.377	0.254	0.005
0218 4E3	20 48 37.401	02.155	20 41 35.689	20 55 39.113	0.567	0.028
0306 1O2	19 47 41.088	02.100	19 46 21.140	19 49 01.036	0.331	0.055
0315 3E4	22 14 43.936	00.787	22 07 05.318	22 22 22.554	0.994	0.016
0320 1O2	23 52 21.334	00.946	23 50 59.892	23 53 42.776	0.163	0.018
0326 2E1	20 40 44.675	04.810	20 39 32.469	20 41 56.880	0.215	0.048
0421 1O2	21 29 04.764	00.725	21 27 37.407	21 30 32.121	0.210	0.021

Here T_0 is moment of event, σ_{T_0} is standard error of T_0, T_1 and T_2 are moments of the beginning and ending of the event, Δmag is maximum brightness drop, $\sigma_{\Delta mag}$ is standard error of Δmag.

Table 3
The results of astrometric observations of occultations.

Data and event 2003	T_0 (UTC) h m s	r_0 arcsec	X_0 arcsec	Y_0 arcsec	V_x arcsec/s	V_y arcsec/s
01 07 2O1	01 25 15.858	1.0270	0.3419	0.9684	-4.9956	1.7634
01 16 4O2	00 43 58.148	0.4907	-0.1546	-0.4657	-12.5194	4.1570
02 03 4O1	17 12 02.918	0.0479	-0.0152	-0.0454	-27.3507	9.1727
02 03 2O3	23 30 49.057	0.3334	0.1058	0.3162	-11.6509	3.8977
02 15 2O1	19 15 56.453	1.0943	-0.3243	-1.0451	-16.4691	5.1112
03 06 1O2	19 47 42.557	0.3506	0.1040	0.3348	31.7936	-9.8765
03 20 1O2	23 52 15.444	0.4524	0.1333	0.4323	30.2036	-9.3120
03 25 2O3	20 47 57.791	0.7415	-0.2022	-0.7133	-16.0298	4.5449
04 01 2O3	23 55 34.990	0.9353	-0.2591	-0.8987	-16.3076	4.7015
04 21 1O2	21 29 05.551	0.3621	0.1062	0.3462	25.5804	-7.8438

Here r_0, X_0, Y_0 are the minimum distances, V_x and V_y are the relative velocities of the satellites.

eters have been estimated. Finally the radius of the nucleus of Hale-Bopp comet has been estimated. It is near 30 km (Yu.N.Gnedin et al., 2001).

The photographic observations of Mercury transit on May, 7 in 2003 have been performed. The aim of these observations was determination of the main parameters of the event: the moment t_0 and the distance ρ_0 of maximum approach of Mercury to the Sun, relative velocity of Mercury μ. These parameters were estimated from the set of distances between images of Mercury and the center of the Sun images. The relative motion during the event was considered as accelerated motion along straight line.The following values of transit parameters have been determined (Kiselev A.A., et al., 2004):

$$t_0 = 7^h 52^m 04.3^s \pm 2.7^s,$$
$$\rho_0 = 703.25 \pm 0.12\, arcsec,$$

$\mu = 0.067477 \pm 0.000033\, arcsec/s.$

These empirical parameters are in a good agreement with the DE405 theory.

6. Conclusions

The analysis of CCD observations with 26-inch refractor with ST6 CCD detector have shown that CCD observations yield to more accurate results of photographic ones. The experience of a long term photographic observations of Solar System bodies provides a basis to develop of CCD astrometry.

Further astrometric investigations of the motions of planetary satellites will be based on CCD observations.

The results of observations of the Solar System bodies obtained with the 26-inch refractor may be used in various astrometric and celestial-mechanics studies owing to their high accuracy, homogeneity, regularity and long term.

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