ISSN 0038-0946, Solar System Research, 2007, Vol. 41, No. 1, pp. 72–80. © Pleiades Publishing, Inc., 2007.
Original Russian Text © T.P. Kiseleva, E.V. Khrutskaya, 2007, published in Astronomicheskii Vestnik, 2007, Vol. 41, No. 1, pp. 77–85.

Pulkovo Astrometric Observations of Bodies in the Solar System from 1898 to 2005: Observational Database

T. P. Kiseleva and E. V. Khrutskaya

Pulkovo Astronomical Observatory, Russian Academy of Sciences, Pulkovskoe sh. 65, St. Petersburg, 196140 Russia

Received February 21, 2006

Abstract—We provide an overview of the main results obtained as part of the programs for astrometric observations of bodies in the Solar system at the Pulkovo Observatory over the period 1898–2005. We summarize the results of photographic observations and show new possibilities for astrometric observations in connection with the transition to CCD detectors on Pulkovo instruments. Observing and data reduction techniques are considered. A database with Pulkovo observations of bodies in the Solar system has been created and opened to users. The database is accessible at http://www.puldb.ru.

PACS numbers: 96.30.-t, 95.75.De, 95.75.Mn, 95.80.+p

DOI: 10.1134/S003809460701008X

INTRODUCTION

Astrometric observations of bodies in the Solar System with the goal of determining their precise coordinates suitable for improving and constructing new theories of motion, improving the orientation of fundamental catalogs, and studying the structure and evolution of the Solar System have been an important subject of Pulkovo astrometric studies since the founding of the Pulkovo Observatory. Photographic observations of these objects were initiated by S.K. Kostinsky, the founder of photographic astrometry in Russia, and were continued by A.N. Deutch, his student and follower, and the staff of the laboratory of photographic astrometry at the Pulkovo Observatory. These observations became particularly active in the post-war period owing to the use of three instruments for observations: a normal astrograph, a 26-inch refractor, and a double short-focus astrograph (AKD), and the development of original observing and data reduction techniques. The observations were performed over the entire 20th century; in the last decade, CCD detectors came to be used to record observations with the 26-inch refractor and the normal astrograph. The long-term work resulted in long, homogeneous series of observations of various bodies in the Solar System: Venus, Mars, Jupiter, Saturn, Uranus, Neptune, Pluto; the satellites of Mars, Jupiter, and Saturn; selected minor planets, asteroids, and comets. Observations were obtained with the highest accessible accuracy and provided a basis for further astrometric studies. With the advent of the space age, astrometric studies of bodies in the Solar System based on positional observations became even more topical because of the need for the ground-based tracking of space projects. At present, despite substantial progress in space observations of certain bodies in the Solar System, ground-based observations remain topical owing to their massiveness, regularity, and considerable duration, as well as the significant increase in their accuracy in connection with the application of new data acquisition techniques and the improvement of observing techniques.

INSTRUMENTS AND OBSERVING PROGRAMS

The following instruments have been used for astrometric photographic observations of bodies in the Solar System at the Pulkovo Observatory:

—Normal astrograph (D/F = 330/3467)

—26-inch refractor (D/F = 650/10413)

—Double wide-field astrograph AKD (D/F = 100/700)

—Lunar–planetary telescope in Ordubad (D/F = 700/10000)

Systematic observations were begun in 1898. These are the observations of Neptune (Lavdovsky, 1974) that were continued until 1955, covering the visibility period of Neptune in Pulkovo. Uranus was observed from 1919 to 1974 (Lavdovsky, 1971). Pluto was observed from its discovery in 1930 until 1996 (Ryl'kov, 1996). From 1904 to 1910, S.K. Kostinsky observed Jupiter's Galilean satellites (Balanovsky, 1916) and the Martian satellites Phobos and Deimos during the favorable opposition in 1909. Satellites of Uranus and Neptune were observed from 1910 to 1922. All these observations were performed with the normal astrograph.

Systematic observations of selected minor planets with the normal astrograph were begun in 1949 with the goal of improving the orientation of the system of the Fundamental Catalog of Faint Stars (CFS, B.V. Numerov's plan). At the suggestion of the Institute of Theoretical Astronomy (ITA), six minor planets were included in the program: Ceres, Pallas, Juno, Vesta, Hebe, and Laetitia. In 1954, four more minor planets were added to this list: Iris, Parthenope, Melpomene, and Harmonia. The choice of these minor planets was determined by their relatively high brightness and uniform distribution in right ascension and declination in the zone from –30° to +30°. Despite unfavorable conditions for the photographic observations of the minor planets in Pulkovo due to the low elevation of the equator, white nights, and poor weather in winter months, 952 plates with the ten minor planets were taken from 1949 to 1964. The observations of the minor planets in this period performed at many observatories worldwide were collected at ITA and MPC (Cincinnati) and reduced to improve the system of the FK4 Catalog. Regular observations of the selected minor planets, whose list was expanded to 20 objects, were continued and have been performed since 1974. A total of ~3000 plates with the minor planets have been taken with the normal astrograph (Deutch, 1966; Kiseleva, 1994).

Regular photographic observations of Mars were begun in 1960 with the double short-focus astrograph AKD (1960–1982) and subsequently also with the normal astrograph (Kiseleva, 1996b). Regular observations of Mars, Jupiter, and Saturn and their satellites with the three instruments were begun in 1972 (Kiseleva, 1996b; Kiseleva et al., 1974). Venus was observed in the period 1960–1970 (Bronnikova and Kiselev, 1973; Kiseleva, 1973). After the first artificial Earth satellite was launched in 1957 in the Soviet Union, observations of artificial satellites were begun in Pulkovo. The observations were performed initially with AKD and subsequently also with new, dedicated cameras (NAFA-3S, AFU-75). Astrophotographs of the rocket carrier of the first satellite were taken for the first time on October 10, 1957, with AKD in Pulkovo; these were used to determine the precise coordinates of the satellite and its brightness variations (Kiseleva, 1957).

Apart from the major planets, their satellites, and selected minor planets, bright comets were regularly observed in Pulkovo as they became visible. In 1985–1986, the observations of Comet Giacobini–Zinner and Halley's Comet were organized in Pulkovo and in expeditions (Ordubad and Bolivia). The latter comet was also observed in Cuba to provide ephemerides for the space mission to Halley's Comet as part of the International Halley Watch and the Soviet Program SOPROG. Pulkovo astrometrists, together with the staff of the Main Astronomical Observatory of the Ukrainian Academy of Sciences, developed methodical procedures for positional observations of comets and their reduction that were used by all observing stations in the Soviet Union (Kiseleva and Mayor, 1984) as part of these projects. The large amount of observational material obtained was promptly transferred to the observational data acquisition centers and was used to improve the orbital parameters of the comet, which was required for the success of the space mission (Kiselev et al., 1990).

The new PHOBOS International Program (1986–1988) was aimed at launching two spacecraft to Mars and required the organization of cooperative observations of the Martian satellites at different astronomical stations. In Pulkovo, Phobos and Deimos were actively observed with all instruments; these objects were also observed in expeditions (Ordubad, Cuba, Bolivia). The material obtained was used to improve the orbits of the Martian satellites (Kiselev and Kiseleva, 1989).

In 1973 and 2003, the transit of Mercury across the solar disk was successfully observed with the 26-inch Pulkovo refractor (Kiselev and Bystrov, 1974; Kiselev et al., 2004).

In 1994, the positional observations of Uranus with the normal astrograph were resumed after a long break due to the invisibility of this planet in Pulkovo.

A new period of observations, the transition from photographic to CCD observations, began in 1995. An ST6 CCD array was mounted on the 26-inch refractor. Changing to the new data acquisition method significantly enhanced the capabilities of the telescope: it increased the limiting magnitude of the telescope, the number of observations, and the accuracy of the results obtained (Izmailov et al., 1998). The program of CCD observations includes the traditional observations of Saturn's main (1–8) satellites and Jupiter's Galilean satellites, as well as observations of occultations and close approaches of asteroids to stars from space catalogs. In 1995–1997, Pulkovo was able to take part in the PHESAT-95 and PHEMU-97 International Programs–CCD observations of mutual events in the satellite systems of Saturn and Jupiter. The experience gained was successfully used in the observations of mutual events in the system of Jupiter's Galilean satellites (2002–2003) as part of the PHEMU-2003 International Program (Izmailov et al., 2004).

In parallel with the CCD observations, photographic observations of Saturn's satellites are also continuing with the instrument. As long-term experience has shown, the photographic observations of satellites of the major planets Jupiter and Saturn with the 26-inch refractor are highly accurate (the internal error is 0.05″–0.10″; the external errors, in comparison with the ephemerides, are 0.07″–0.15″) and allow the entire system of Saturn and the system of Jupiter's Galilean satellites to be obtained on a single photographic plate, while only 2 or 3 satellites can be obtained on CCD frames (because the CCD field is small: 3′ × 2′). Saturn's satellites 1–6 and 8 have been obtained in the photographs taken with the 26-inch refractor. Satellite 7, Hyperion (14.5 mag), has been obtained only on CCD frames (Kiseleva, 2004).

In December 2004, a CCD array produced by the Electron Optronik Company (S2C-017AP) was mounted on the normal astrograph. The working CCD field is 18′ × 16′, the pixel size is 16 × 16 μm, and the number of effective pixels is 1040 × 1160. At present, the investigation and calibration of the CCD array have

Brief characteristic of the Pulkovo observations of bodies in the Solar system

Objects	Type of observations	Observing period	Estimate of accuracy, arcsec	Type of coordinates
Selected minor planets (15 planets)	Photo	1957–2002	0.20–0.40	α, δ
Faint asteroids (13 asteroids)	CCD	2005	0.07–0.19	α, δ
Comet Halley	Photo	1985–1986	0.60–1.5	α, δ
Comet Hale–Bopp	Photo	1997	0.36	α, δ
Comet Machholz	Photo	2004–2005	0.10	α, δ
Venus	Photo	1969, 1972	0.40	α, δ
Mars	Photo	1960–1982	0.30–0.40	α, δ
Martian satellites – Phobos and Deimos	Photo	1973, 1982, 1986, 1988	0.30–0.50	α, δ *X*, *Y*
Jupiter	Photo	1974–1978	0.30–0.40	α, δ
Galilean satellites of Jupiter	Photo	1976–2004	0.10–0.30	α, δ *X*,*Y*
Saturn	Photo	1971–2004	0.12–0.30	α, δ
Satellites of Saturn (1–8)	Photo CCD	1973–2005 1995–2005	0.12–0.30 0.07–0.20	*X*, *Y*
Uranus	Photo	1919–2004	0.30–0.40	α, δ
Satellites of Uranus (3, 4)	Photo	1987–1994	0.30–0.40	α, δ; *X*,*Y*
Neptune	Photo	1899–1955	0.25	α, δ
Pluto	Photo	1930–1996	0.25	α, δ

been finished, the test observations of asteroids and Comet Machholz have been carried out, and a new program for regular observations of bodies in the Solar System has been developed (Khrutskaya and Khovrichev, 2006). The program includes the observations of selected minor planets, binary asteroids (including the search for binary asteroids), Earth-approaching asteroids as part of the program of asteroid–comet hazards, approaches and occultations, and faint satellites of the major planets. Photographic observations with the normal astrograph were ceased in 2005.

The table presents a brief characteristic of the Pulkovo observations of bodies in the Solar System. The "estimate of accuracy" column gives the rms errors of the observations that the authors of the corresponding works calculated from external convergence with the ephemerides that were taken as the most recent ones when the observational data were reduced. More complete information about the observations can be found in the description of the Pulkovo database of astrometric observations of bodies in the Solar System.

OBSERVING AND DATA REDUCTION TECHNIQUES

During the observations, filters were used to reduce the brightness of the planetary images on photographic plates. The film filters were used for the first time during the AKD observations. Subsequently, the film filters were replaced with the glass and evaporated aluminum filters produced at the optical workshop of the Pulkovo Observatory. The filters were several millimeters in diameter and were placed in the central part of the field of view immediately in front of the photographic plate, reducing the brightness of only the planet and without changing the brightness of the reference stars. Thus, the brightness of the planet was reduced approximately to the brightness of the reference stars. Relatively short (1–2 min) exposures were used in photographing to avoid planetary image extension. Guiding was used at long exposures. Several (3–10) exposures were always taken on one plate to reduce the random measurement error. In addition, when minor planets were observed, the change in the position of the planet from exposure to exposure allowed the moving object to be easily identified against the stellar background. The result from the plate with several exposures was averaged, so one Pulkovo observation is always the mean of several positions on the photographic plate.

The need to obtain high-accuracy observations required a continuous improvement of the observational data reduction technique. This primarily concerns the necessity of allowing for the traditional systematic errors that arise in photographic observations: differential refraction, atmospheric dispersion, and other distortions of the projection. When the observations of major planets were reduced, it was necessary to take into account the planet's phase and the effects that introduce photographic expansion of the extended image and photometric inhomogeneities of the planetary disk when the center of the photographic image of the planet is determined.

Observations with the 26-inch refractor (the working field is 30′ in diameter) gave impetus to the development of long-focus astrometry. In this connection, Kiselev developed a theory of photographic astrometry that includes astrometric data reduction methods for observations with both long-focus and wide-field instruments (double referencing, scale-trail, dependences, etc.) and methods for investigating the distortion of the central projection of the field of telescopes (Kiselev, 1989).

When planets and their satellites are observed, correction for the phase effect poses a major problem. Generally, the corrections have been calculated by various authors according to the theoretical laws of light reflection from the surface of a planet (geometrical, orthotropic, mirror, etc.) chosen on the basis of ideas about the physical properties of the planetary surface and the properties of the telescope's objective. However, these phase correction methods generally did not yield a complete correction of this effect (Ryl'kov and Dement'eva, 1995). When long series of observations of planets and their satellites are available, it becomes possible to determine the phase error directly from observations. Kiseleva (1985) developed a technique for correcting the phase effect of a planet from the observations of satellites relative to the planet. It was shown that, in those cases where the satellites are at different elongations relative to the planet, their positions are subject to the same phase error, but with the opposite sign. In this case, the double phase correction is represented as the (O–C) residual for these two satellites. For long series of observations, such situations in the arrangements of satellites are encountered often. This method for determining the phase effect was used to determine the Jovicentric coordinates of Jupiter's Galilean satellites from observations with the 26-inch refractor (1976–2004) and with the normal astrograph (1904–1910, 1977–1978) and yielded good results (Kiseleva, 1996a; Kiselev and Kiseleva, 1989).

The photographing of check stars from the FK4 and FK5 Fundamental Catalogs in parallel with the main observations of planets was suggested and widely used to check the accuracy of the photographic observations in Pulkovo. After the appearance of space catalogs, check stars were chosen directly from among the field stars near the planet itself, and their positions were determined along with the planet's position in the system of the same reference stars. The following catalogs were used at different times as references: Yale Catalogs, AGK3, PPM, GSC, TYCHO, ACT, TYCHO-2, and UCAC2. We deliberately avoided using the SAO Catalog in our astrometric reduction, because the accuracy of its coordinates is low (the same applies to the USNO Catalog). We gave preference to the method of six constants as a method of astrometric reduction from reference stars, since it yields the best result at the plate center (Kiselev, 1989) for small fields (~1° in diameter). In large fields (in the case of AKD observations), the methods of homographic coordinates and the method of eight constants (Kiseleva, 1970) were used for the reduction.

In the absence of a sufficient number of reference stars in the working field, the scale-trail technique was used to reduce the photographic observations of satellites. In this case, no reference stars are required for the reduction, the orientation of the measurements is determined using the daily tracks of satellites on photographic plates, and the scale is specified by taking into account the temperature and pressure based on a special study of the telescope's scale. This technique yields highly accurate positions of satellites if the distances between the satellites and the planet are moderately large (no more than 100″).

A technique for determining the coordinates of a planet from the observations of its satellites without measuring the planet images on photographic plates or in the field of a CCD camera has been developed. The planet coordinates obtained in this way do not depend on the image-related errors such as image extension, photometric inhomogeneity, atmospheric fluctuations, and the planet phase, which is the largest and most difficult to determine error in the positions of planets. To determine the positions of planets with a high accuracy by this method, we must have at least 3 reference stars in the field of a plate or a CCD frame and a fairly accurate ephemeris of the planet's satellites. The coordinates of Jupiter and Saturn were determined by this method with an accuracy of 0.1″ or higher (Kiseleva et al., 2004).

Using a CCD array with the normal astrograph and the 26-inch refractor fostered the development of new data reduction methods. Izmailov et al. (1998) suggested an original technique for determining the center of CCD images. An optimal model for determining the center of a CCD image includes the effect of the background gradient on the positions of satellites near a bright planet during observations with a long-focus telescope. This technique provides an internal positional accuracy of ~0.001″–0.005″ within a series of CCD frames. A new technique has been developed for the calibration and astrometric reduction of CCD observations that uses the observations of stars from the TYCHO-2 Space Catalog over the entire sky and near the observed object to determine the parameters of the CCD scale and orientation. Based on the developed reduction technique for CCD observations, Izmailov (2005) developed the IZMCCD software package (http://www.izmccd.puldb.ru). The package is designed to measure digital images and to determine highly accurate coordinates of objects by various methods (with reference or calibration stars, if there are no reference stars from the space catalog in the CCD field of view). It is possible to identify already known minor planets and to detect new rapidly moving objects like Earth-approaching asteroids.

A technique for CCD observations of approaches and occulations of stars from space catalogs by asteroids has been developed. As a result of such observations, the ephemerides of minor planets can be checked with a high accuracy (Kiseleva et al., 2002).

All of the developed techniques allow both photographic and CCD observations to be performed at the international level of accuracy. The techniques in the field of photographic and CCD observations are used to observe bodies in the Solar System at other observatories both in Russia and abroad.

MAIN RESULTS

(1) The main result of the photographic observations is the long series of observations of various bodies in the Solar System: the major planets and their satellites, selected minor planets, and comets. Observations were performed with the same instruments using homogeneous observing and data reduction techniques. To check the results of the observations and analyze their accuracy, all observations were compared with the ephemerides calculated on the basis of modern theories of motion. The (O–C) residuals in the sense "observation minus ephemeris" allow the observational errors and the errors in the theories of motion to be estimated. At the current level of accuracy of the observations and theories, these residuals make it possible to compare the coordinate systems: the dynamical one realized by ephemerides and the cosmic one (ICRS) realized by currently available highly accurate space catalogs. At present, this objective is particularly topical in connection with the intensively developing space observations of bodies in the Solar System.

(2) A detailed comparison of the observations of Pluto (211 positions, 1930–1994) with the ephemerides DE200 and DE202 revealed errors in the theory of motion. The corrections to the orbital elements of Pluto were calculated on the basis of the Pulkovo series. The positional accuracy is estimated to be 0.3″ (Ryl'kov, 1996). The homogeneous Pulkovo series of observations of Pluto allowed one to detect and investigate the secular change in brightness of Pluto (0.36 mag in 36 years) in the interval 1954–1990 and brightness variations with a period of 7–8 years (Bronnikova, 1992).

(3) Based on a multifactor analysis, Kiseleva (1994) determined the systematic errors of the AGK3 Catalog (in whose system the observations were reduced) and showed that the accuracy of the ephemerides could be estimated from the observations of minor planets near the points of intersection of their apparent trajectories in the sky by comparing the observations of 14 selected minor planets (1974–1994) with the current ephemerides.

(4) The astrometric studies of satellites systems of Jupiter and Saturn, the Galilean satellites of Jupiter and the eight main satellites of Saturn, are an important result. More than 30 years of positional observations with the 26-inch refractor and the normal astrograph in the visibility periods of the planets in Pulkovo (1973–2006) have been devoted to this work. The highly accurate positions thus derived are suitable for improving the theories of satellite motion and investigating the evolution of the satellite systems and the Solar System as a whole. The results of the observations are the relative coordinates of the satellites ("satellite minus planet" and "satellite minus satellite") and their equatorial coordinates obtained on the normal astrograph with the AGK3 Catalogs and, in recent years, also on the 26-inch refractor with respect to the reference stars from space catalogs. The accuracy of the photographic observations with the normal astrograph before 1995 is 0.2″ for the equatorial coordinates. The accuracy of the "satellite minus satellite" relative coordinates obtained from observations with the 26-inch refractor is currently 0.05″–0.1″. The various systematic effects affecting the accuracy of photographic and CCD observations, the main of which are the phase errors and the reduction errors in the scale-trail method, were investigated. A systematic error of ~0.2″–0.4″ was found in the planetocentric coordinates of the planets; it arises when the extended photographic image of the planet is measured. It was concluded that it is preferable to determine the mutual relative coordinates of the satellites. A new reduction technique for CCD observations was developed on the basis of the performed studies; it does not use the tracks of satellites in determining the orientation parameter and is based on the observations of TYCHO-2 check stars near the objects being determined. The accuracy of the CCD observations of Saturnian satellites increased to 0.02″–0.05″ (Kiseleva, 2004; Izmailov et al., 2004). The positions of the planets were determined from the observations of satellites based on the observations of Saturn's and Jupiter's satellites without measuring the planetary images in photographs with an error no larger than 0.15″ (Kiseleva et al., 2004).

(5) Dense series of positions of Phobos and Deimos, both relative (satellite–satellite) and stellar (RA, DEC), were obtained near a favorable opposition of Mars (1988) with the lunar–planetary telescope in Ordubad and with the 26-inch refractor and the normal astrograph in Pulkovo as part of the PHOBOS International Program. The error in the satellite positions was 0.3″–0.4″ (Kiselev and Kiseleva, 1989; Bobylev et al., 1991). Shor (1988) used the Pulkovo positions to improve the theory of motion of the Martian satellites.

(6) In the field of cometary astronomy, the observations of Comet Hale–Bopp with the 26-inch refractor (1997, 55 precise positions of the comet head with an error of no more than 0.35″) revealed an interesting structure of the comet head: several gradually fading concentric envelopes around the nucleus and jets of dust and gas from the nucleus. The dust grain masses and sizes were estimated from the measurements of these photographs. It was concluded that submicron-

sized grains predominate in the envelopes of the comet head. The characteristic activity time of the comet head, the initial velocity of the ejected dust grains, and the ratio of the radiation pressure force exerted on dust grains to the force of their gravitational attraction to the Sun were estimated. The observations allowed the radius of the comet nucleus to be estimated as ~30 km (Gnedin et al., 2001; Kiseleva et al., 1998).

Based on the observations of Comet Machholz with the normal astrograph equipped with a CCD array in 2004–2005, Khrutskaya et al. (2005) obtained a series of positions of the comet with an accuracy of 0.1″.

(7) The Pulkovo observations of Halley's Comet contributed significantly to the success of the Vega-1 and Vega-2 Space Missions. The contribution of the Pulkovo Observatory and its expeditions to the Soviet database of positional observations of Halley's Comet was 12.3%. The accuracy of the Pulkovo observations, ~1″ in the comet positions, corresponds to the accuracy of the results obtained worldwide (Kiselev et al., 1990). A total of 2700 observations of the comet were performed at 35 stations in the Soviet Union. These observations allowed the comet orbit to be determined so accurately that the error in the time of the spacecraft rendezvous with the comet did not exceed 10–20 s, which was quite sufficient for the success of the Vega Program.

(8) The observations of Mercury's transit across the solar disk with the 26-inch refractor in 1973 and 2003 (Kiselev and Bystrov, 1974; Kiselev et al., 2004) were used to determine the minimum distance between the Sun and Mercury with an error of 0.12″ and the time of the closest approach with an error of 2.7 s. The observations were compared with Mercury's ephemeris and confirmed its high accuracy.

(9) Changing to CCD observations with the 26-inch refractor (in 1995) and with the normal astrograph (in 2005) significantly enhanced the capabilities of the telescopes by increasing the limiting magnitude and the number of observed objects. The developed original techniques for determining the center of CCD images and their calibration considerably increased the observational accuracy and allowed highly accurate series of observations of planetary satellites, asteroids, and comets to be obtained with the normal astrograph and the 26-inch refractor of the Pulkovo Observatory. At present, the accuracy of the results on both instruments is, on average, 20–50 mas.

(10) The CCD observations of approaches and occultations of stars from space catalogs by asteroids performed with the 26-inch refractor in 1998–2001 provide material for comparing the dynamical and cosmic coordinate systems. Since the positions of stars in the currently available catalogs are highly accurate, these observations allow one to improve the orbital elements of asteroids and to obtain the corrections to their ephemerides. When the approach of asteroid no. 454 to a star from the GSC catalog was analyzed, it proved to be possible to obtain a photometric light curve of the asteroid relative to the star. Based on the amplitude of this light curve, Kiseleva et al. (2002) were able to estimate the rotation period of the asteroid, 4 hours.

(11) The photometric and astrometric CCD observations of mutual events in the system of Jupiter's Galilean satellites performed in 2003 as part of the PHEMU-2003 Program yielded light curves for 20 occultations and eclipses. The times of the closest approaches, the event durations, and the brightness declines were determined (Izmailov et al., 2004). Based on the light curves, N.V. Emel'yanov determined the minimum distances between the satellites involved in an event with an accuracy of ~0.012″, which is much higher than the accuracy of astrometric distance measurements.

DATABASE WITH THE OBSERVATIONS OF BODIES IN THE SOLAR SYSTEM

To make it possible for the observations of bodies in the Solar System to be widely used in various astrometric and celestial-mechanics studies, a database with the results of Pulkovo observations has been created and opened to users. This database is accessible to users at http://www.puldb.ru. This is the second of the three astrometric databases in which the Pulkovo observations are presented.

* The first database contains the Pulkovo photographic catalogs (Khrutskaya et al., 2004).

* The second database contains the photographic and CCD observations of bodies in the Solar System (Khrutskaya et al., 2005)

* The third database contains the photographic and CCD observations of selected double and multiple stars and stars with invisible satellites.

At present, the first and second databases are open to users; the third database is under construction. According to the plan, the third database will be accessible to users in the fall of 2006.

The database with the observations of bodies in the Solar System consists of two sections: major planets and their satellites and small bodies of the Solar System (asteroids and comets). The database includes all of the observations obtained to date.

Having chosen an appropriate section in this database, the user chooses an object of interest and a time interval. If no years of observations are specified, then all the available observations of the selected object will be chosen. Subsequently, going to a web form with additional characteristics of the object (the Sent request key at the site), the user can refine the selection—more specifically, the user may choose the instrument with which the observations were performed, the type of observations (photo or CCD), and select the output data by taking only those needed by the user (all data are provided by default).

Depending on the type of observations (with or without reference stars), both equatorial coordinates of the object (α, δ) in the system of the reference catalog and relative positions of the satellites ($X = \Delta\alpha\cos\delta$, $Y = \Delta\delta$) with respect to the planet or another satellite can be given for the satellites of the major planets. It is possible to choose the data pertaining to a certain type of observations.

Data are accessed via scripts written in the PHP language that implement an interface with the MySQL database. The retrieved data are text files.

For convenience, the users can view the data format and familiarize themselves with a general characteristic of the observations for specific objects in each web form in the Info Section. The general characteristic provides the following information for each object: telescope, observing period, type of observations, type of coordinates (α, δ or X, Y), reference catalog, epoch and equinox, origin (topocentric or heliocentric coordinates), rms errors, source of the ephemeris from which (O–C) was calculated, and number of the publication given in the List of Publications section for objects. This section gives full references to the published papers. Full text can be retrieved for most papers of a methodological content (from the section entitled "Papers Containing Description of Observational Data Reduction Techniques").

The created database will be supplemented by new observations. The regularly updated pages with estimates of the accuracy of CCD observations for minor planets from observations with various telescopes worldwide can be viewed from the first page of the site.

CONCLUSIONS

This paper summarizes the results of the photographic positional observations of bodies in the Solar System that were performed at the Pulkovo Observatory during the 20th century and that are a major objective of observational astrometry in Pulkovo. Results of the maximum possible accuracy have been achieved in this field of astrometry in Pulkovo. Photographic methods are currently being replaced with CCD methods everywhere. The Pulkovo Observatory is no exception in this respect. At present, the photographic observations have completely ceased on the normal astrograph and are being finished on the 26-inch refractor. The experience of 10-year-long CCD observations with the 26-inch refractor and the first observations with the normal astrograph (as well as international experience) has shown that CCD observations yield more accurate results than photographic observations. However, it should be noted that the experience of photographic observations of bodies in the Solar System gained in Pulkovo provides a basis for the development of CCD astrometry. Many methods of photographic astrometry are also applicable to the reduction of CCD observations. This concerns CCD field investigation, CCD calibration, measurements of the images of celestial objects on CCD frames, astrometric reduction, and all of the further astrometric studies of the motions of bodies in the Solar System based on CCD observations.

At present, a list of programs for astrometric observations of bodies in the Solar System in the coming years using CCD detectors has been compiled, and their implementation has begun. The observing programs include the following:

* observations of the main satellites of major planets;

* observations of faint satellites of planets;

* continuation of the observations of 20 selected minor planets;

* observations of presumably binary faint asteroids;

* observations of Earth-approaching asteroids;

* observations of apparent approaches and occultations of stars by asteroids;

* observations of mutual events in the systems of planetary satellites;

* observations as part of the program for the ground-based tracking of the GAIA space project.

The implementation of the above observing programs is accompanied by the improvement of available observing and data reduction techniques and by the development of new ones. Carrying out these programs provides further astrometric and celestial-mechanics studies based on the Pulkovo observations of bodies in the Solar System.

ACKNOWLEDGMENTS

The astrometric studies based on the observations of bodies in the Solar System are currently supported by the Russian Foundation for Basic Research (project no. 04-02-16157). The work to create the astrometric database of bodies in the Solar System was supported by the Russian Foundation for Basic Research (project no. 04-07-90081).

REFERENCES

Balanovsky, I., Positions des satellites de Jupiter deduites d'apres les cliches obteuns par M. Kostinsky a Poulkovo pendant les oppositions de 1904–1910, *Tr. Gl. Astron. Obs.*, 1916, vol. 31, pp. 3–95.

Bobylev, V.V., Evdokimov, A.E., Kalinichenko, O.A., et al., Positional Photographic Observations of the Martian Satellites Made at Pulkovo and Ordubad in 1988, *Izv. Gl. Astron. Obs.*, 1991, no. 207, pp. 37–43.

Bronnikova, N.M. and Kiselev, A.A., Photographic Observations of Venus Made at Pulkovo with the 26-Inch Refractor, *Izv. Gl. Astron. Obs.*, 1973, no. 191, pp. 148–163.

Bronnikova, N.M., Investigation of Pluto Brightness, in *Astrofotografiya v issledovanii Vselennoi* (Astrophotography in Investigation of the Universe), St. Petersburg: GAO RAN, 1992, pp. 226–247.

Chanturiya, S.M., Kiseleva, T.P., and Emel'yanov, N.V., Photographic Positional Observations of Uranus and Its Satellites Titania and Oberon at Abastumani in 1987–1994, *Izv. Gl. Astron. Obs.*, 2002, no. 216, pp. 349–362.

Deich, A.N., Results of Observations of Small Planets at Pulkovo, *Izv. Gl. Astron. Obs.*, 1966, vol. 24, no. 179, pp. 162–166.

Gnedin, Yu.N., Kiselev, A.A., Kiseleva, T.P., and Maslennikov, K.L., Photographic Observations of Comet Hale–Bopp at the Pulkovo Observatory: The Detection of Dust Envelopes, *Pis'ma Astron. Zh.*, 2001, vol. 27, no. 4, pp. 291–295 [*Astron. Lett.* (Engl. Transl.), vol. 27, no. 4, pp. 249–253].

Izmailov, I.S., Kiselev, A.A., Kiseleva, T.P., and Khrutskaya, E.V., Using a CCD Camera in Pulkovo Programs of Observations of Binary and Multiple Stars and Satellites of Major Planets with the 26-Inch Refractor, *Pis'ma Astron. Zh.*, 1998, vol. 24, no. 10, pp. 772–779 [*Astron. Lett.* (Engl. Transl.), vol. 24, no. 10, pp. 665–672].

Izmailov, I.S., Khovritchev, M.Yu., Khrutskaya, E.V., and Kiseleva, T.P., CCD-Observations of Galilean Satellites of Jupiter during Their Mutual Occultations and Eclipses in 2003 at the Pulkovo Observatory, *JOURNÉES-2003, "Astrometry, Geodynamics and Solar System Dynamics: from Milliarcseconds to Microarcseconds"*, St. Petersburg: 2004, pp. 269–274.

Khrutskaya, E.V., Khovritchev, M.Yu., and Izmailov, I.S., System of Astrometric Databases of the Pulkovo Observatory: Photographic Catalogues and Estimates of Accuracy of Present-Day CCD-Observations of Small Planets, *Izv. Gl. Astron. Obs.*, 2004, no. 217, pp. 343–349.

Khrutskaya, E.V., Khovritchev, M.Yu., and Izmailov, I.S., The Observations of Machholz Comet in 2004-2005 Years at the Pulkovo Observatory, *Minor Planet Circ.*, 2005a, no. 2, 54797.

Khrutskaya, E.V., Khovritchev, M.Yu., and Kalinin, S.I., The First Results of CCD Observations of Solar System Minor Bodies with the Pulkovo Normal Astrograph and the Astrometric Database of the Solar System Bodies at the Pulkovo Observatory, *Materialy mezhdunar. konf. "Asteroidno-kometnaya opasnost'-2005"* (Proc. Int. Conf. "Asteroid-Comet Hazard-2005"), St. Petersburg: 2005b, pp. 328–331.

Khrutskaya, E.V., Khovritchev, M.Yu., and Berezhnoj, A.A., First Results of CCD-Observations of the Solar System Minor Bodies with the Normal Astrograph of the Pulkovo Observatory and Planned Observations, *Izv. Gl. Astron. Obs.*, 2006, no. 218 (in press).

Kiselev, A.A. and Bystrov, N.F., Photographic Observations of Mercury Passage along the Disk of the Sun on 10 November 1973 Made at Pulkovo with the 26-Inch Refractor, *Izv. Gl. Astron. Obs.*, 1974, no. 194, pp. 139–148.

Kiselev, A.A., *Teoreticheskie osnovaniya fotograficheskoi astrometrii* (Theoretical Bases of Photographic Astrometry), Moscow: Nauka, 1989.

Kiselev, A.A. and Kiseleva, T.P., Results of Observations of the Martian Satellites with the Lunar-Planetary Telescope in the Ordubad Expedition of the Main Astronomical Observatory of the USSR Academy of Sciences in 1986, *Izv. Gl. Astron. Obs.*, 1989, no. 206, pp. 33–39.

Kiselev, A.A., Bobylev, V.V., Bronnikova, N.M., et al., Results of Positional Photographic Observations of Comet Halley Made at Pulkovo and in Expeditions of the Main Astronomical Observatory of the USSR Academy of Sciences in 1985–1986, in *Pozitsionnye nablyudeniya v SSSR komety Galleya v poyavlenii 1986 g* (Positional Observations in USSR of Comet Halley at its Appearance in 1986), Kiev: Naukova Dumka, 1990, pp. 36–45.

Kiselev, A.A., Kiseleva, T.P., Izmailov, I.S., et al., Photographic Observations of the Mercury Passage along the Solar Disk on May 7, 2003 Made at Pulkovo with the 26-Inch Refractor, *Izv. Gl. Astron. Obs.*, 2004, no. 217, pp. 269–274.

Kiseleva, T.P., Photographic Observations of an Artificial Satellite of the Earth Made at Pulkovo with AKD, *Astron. Tsirk.*, 1957, no. 186.

Kiseleva, T.P., Photographic Positions of Mars Obtained with a Double Short-Focus Astrograph of the Pulkovo Observatory in 1962–1965, *Izv. Gl. Astron. Obs.*, 1970, no. 185, pp. 98–102.

Kiseleva, T.P., Positional Photographic Observations of Venus at Pulkovo with AKD in 1969, *Izv. Gl. Astron. Obs.*, 1973, no. 191, pp. 164–166.

Kiseleva, T.P., Kalinichenko, O.A., and Panova, G.V., Positional Photographic Observations of Saturn and Its Satellites in 1971–1974 Made at Pulkovo with Three Instruments, *Izv. Gl. Astron. Obs.*, 1974, pp. 49–66.

Kiseleva, T.P. and Maior, S.P., *Pozitsionnye nablyudeniya. Rekomendatsii k nablyudeniyam komety Galleya v 1985–1986 gg* (Positional Observations. Recommendations for Comet Halley Observations in 1985–1986), Kiev: Inform. Soobshch. Inst. Teor. Fiz., 1984.

Kiseleva, T.P., Photographic Observations of the Galilean Satellites of Jupiter in 1904–1910 at Pulkovo: Comparison with Theory and Analysis, *Izv. Gl. Astron. Obs.*, 1985, no. 201, pp. 71–76.

Kiseleva, T.P., Results of Observations of Minor Planets Made at the Pulkovo Observatory with the Normal Astrograph in 1974–1990, *Izv. Gl. Astron. Obs.*, 1994, no. 209, pp. 76–88.

Kiseleva, T.P., Astronomical Observations of the Galilean Satellites of Jupiter at Pulkovo with the 26-Inch Refractor, *Izv. Gl. Astron. Obs.*, 1996a, no. 210, pp. 11–43.

Kiseleva, T.P., Astronomical Investigation of Series of Photographic Observations of Mars, *Izv. Gl. Astron. Obs.*, 1996b, no. 210, pp. 44–48.

Kiseleva, T.P., Kiselev, A.A., Izmailov, I.S., et al., Observations of Comet Hale–Bopp with the 26-Inch Refractor at Pulkovo in 1997, *Izv. Gl. Astron. Obs.*, 1998, no. 213, pp. 176–179.

Kiseleva, T.P., Izmailov, I.S., and Mozhaev, M.A., Observations of Close Approaches and Occultations of Stars by Asteroids at the Pulkovo Observatory with the 26-Inch Refractor with CCD, *Izv. Gl. Astron. Obs.*, 2002, no. 216, pp. 181–184.

Kiseleva, T.P., Analysis of Systematic Errors in the Scale and Orientation during Photographic and CCD Observations of the Main Satellites of Saturn at Pulkovo in 1995–2003 with the 26-Inch Refractor, *Izv. Gl. Astron. Obs.*, 2004, no. 217, pp. 286–291.

Kiseleva, T.P., Kalinichenko, O.A., and Mozhaev, M.A., Photographic Observations of Saturn's Satellites with the 26-Inch Refractor in 2001–2003 at Pulkovo. Determination of Coordinates of Saturn from Observations of Its Satellites, *Izv. Gl. Astron. Obs.*, 2004a, no. 217, pp. 297–305.

Kiseleva, T.P., Izmailov, I.S., Khovritchev, M.Yu., and Khrutskaya, E.V., Results of CCD Observations of Jupiter's and Saturn's Satellites in 2004 with the 26-Inch Refractor at Pulkovo, *Izv. Gl. Astron. Obs.*, 2004b, no. 217, pp. 292–296.

Lavdovskii, V.V., Precise positions of Uranus for 1919–1969 from photographic Observations at Pulkovo and Tashkent, *Izv. Gl. Astron. Obs.*, 1971, no. 189–190, pp. 140–143.

Lavdovskii, V.V., Precise positions of Neptune for 1899-1955 from photographic Observations at Pulkovo and Tashkent, *Izv. Gl. Astron. Obs.*, 1974, no. 192, pp. 33–45.

Ryl'kov, V.P. and Dement'eva, A.A., Consideration of Corrections for the Phase in the Processing of Positional Observations of Mars in 1973–1993, *Astron. Vestn.*, 1995, vol. 29, no. 6, pp. 506–515 [*Sol. Syst. Res.* (Engl. Transl.), 1995, vol. 29, no. 6, p. 441–449].

Ryl'kov, V.P., Pluto: Positions for 1930–1994, New Elements of the Orbit and Analysis of Differences (O–C), *Izv. Gl. Astron. Obs.*, 1996, no. 210, pp. 52–67.

Shor, V.A., Refinement of the Orbits of Phobos and Deimos Using Ground and Spacecraft Observations, *Pis'ma Astron. Zh.*, 1988, vol. 14, no. 12, pp. 1123–1130 [*Sov. Astron. Lett.* (Engl. Transl.), vol. 14, no. 6, p. 477].