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Astrometrical observations of Pluto–Charon system with the automated telescopes of Pulkovo observatory

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ABSTRACT

The space probe "New Horizons" was launched on 19th of January 2006 in order to study Pluto and its moons. Spacecraft performed close fly-by to Pluto on 14th of July 2015 and obtained the most detailed images of Pluto and its moon until this moment. At the same time, observation obtained by the ground-based telescopes may also be helpful for the research of such distant system. Thereby, the Laboratory of observational astrometry of Pulkovo Observatory of RAS made a decision to reprocess observations obtained during last decade. More than 350 positional observations of Pluto–Charon system were carried out with the mirror astrograph ZA-320M at Pulkovo and Maksutov telescope MTM-500M near Kislovodsk. These observations were processed by means of software system APEX-II developed in Pulkovo observatory and numerical simulations were performed to calculate the differences between positions of photocenter and barycenter of Pluto–Charon system.

1. Introduction

From 1999 till 2010 the Laboratory of observational astrometry of Pulkovo observatory was carrying out regular astrometrical observations of the Pluto–Charon system (Devyatkin et al., 2006). For the period from May 1999 till August 2006 the observations were performed with the mirror astrograph ZA-320 ($D=320$ mm, $F=3200$ mm) (Devyatkin et al., 2009), equipped with CCD camera SBIG ST-6 (1999–2004) and CCD camera FLI IMG 1001E (2005–2006). The observations were carried out preferably near the meridian at the hour angle not exceeded $\pm 1^{h}$. The zenith angle of Pluto was about 70° due to the declination of Pluto and latitude of the observatory (Pulkovo, Saint-Petersburg, Russia). The expositions between 60 and 200 s were used to collect enough light. Total amount of positional observations with ZA-320 M for this period is 164. Due to the decrease of Pluto's declination, observations with ZA-320 M had to be terminated, but they were resumed on June 2008 with the new telescope MTM-500 M ($D=500$ mm, $F=4100$ mm) equipped with CCD camera SBIG STL 1001E and located on the lower latitude near the city of Kislovodsk (Northern Caucasus, Russia) (Kulish et al., 2009a, 2009b). For the period from June 2008 till August 2010 total amount of 248 observations was obtained by means of this equipment.

2. Analysis of observations

For a current time ground-based astrometrical observations with CCD cameras allow calculating the position of the celestial bodies with an accuracy about 0″.01 (Bely, 2003). In order to reach such accuracy it is necessary to calculate the corrections, caused by the geometrical and photometrical features of observable objects. For the observations performed on the mid-sized telescopes such as ZA-320M and MTM-500M, it is impossible to separate the images of two components of Pluto–Charon system, therefore only the position of photocenter can be derived from obtained image frames. This issue dramatically limits the accuracy of the observations, however their careful analysis allowing the significant decrease of the uncertainty in Pluto and Charon positions. Recently, more than 2500 photographic and CCD observations of Pluto, covering the timespan from 1914 to 2010, were analyzed and fitted by new ODIN (Orbite, Dynamique et Intégration Numérique) model, which takes into account not only Pluto and Charon, but also Nix and Hydra (Beauvalet et al., 2013). The observations considered in mentioned paper include photographic data from Pulkovo astrograph for the period from 1930 to 1993 (Rylkov et al., 1995), however this paper does not include the most recent observations, made in Pulkovo Observatory, because these observations have not been published yet.

Total amount of 359 positional observations have been taken for the period from 1999 to 2010 by means of ZA-320M and MTM-500M telescopes. Processing of obtained images was performed

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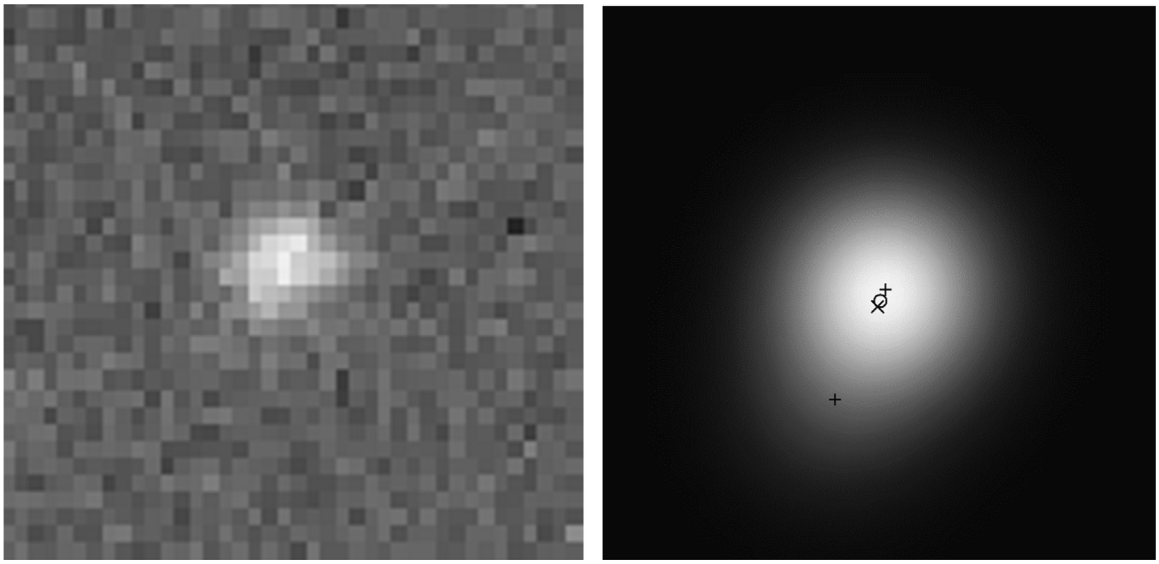

Fig. 1. Real (left) and simulated (right) images of Pluto–Charon system for 27th March 2003 (not in the same scale). "+" symbols represent centers of the dwarf planets, "×" and "o" – photocenter and barycenter of the system respectively.

with a help of the software system APEX-II (Devyatkin et al., 2010) developed in Pulkovo observatory. Depending on the observation's conditions, from 8 to 450 reference stars from recently published UCAC4 catalog (Zacharias et al., 2013) were chosen on each image frame. In order to take into account the difference between the positions of barycenter and photocenter of Pluto–Charon system, the distance between centers of Pluto and Charon as well as positional angle of Charon on the geocentric celestial sphere were determined for a specific time moments. These calculations were implemented by means of software system EPOS8 developed in Pulkovo observatory (L'vov and Tsekmeister, 2012). Then obtained data were used to simulate the image of the Pluto–Charon system for time moment of each real observation by the means of the following method.

It is not possible to obtain sharp images of minor planets with a help of ground-based observations due to limited angular resolution and atmospheric fluctuations. In order to take these factors into consideration, the visible distributions of the illumination of Pluto or Charon $L(x, y, t)$ at the (x, y) point on image frame for the time moment t can be factorized like

$$L(x, y, t) = L_0(t)H(x, y), \tag{1}$$

where the first multiplier $L_0(t)$ reflects the real magnitude of the component for specific moment of time, while second one $H(x, y)$ represents the distortion of the image due to the atmospheric fluctuations. Note, that such factorization is possible only for the case of homogeneously reflecting object; otherwise Eq. (1) becomes more complex. Due to nonhomogeneous albedo of the surfaces of Pluto and Charon (Stern et al., 2015), this assumption cannot be made for observations, carried out by means of space-based or ground-based large aperture telescopes. At the same time, for middle or small sized ground-based telescopes this approximation is applicable due to their low resolution. Nevertheless, the variations of Pluto and Charon albedo should be taken into account by means of function $L_0(t)$, which represents the variation of magnitude for Pluto–Charon components. In simulation we used the lightcurve for Pluto and Charon after removing the phase variation by means of linear phase coefficients 0.0294 and 0.0866 for Pluto and Charon, respectively (Buie et al., 1997). The solar phase angle during observation period was changed in 0.2-2.0 degree range, however it was earlier shown that opposition surge effect for Pluto is not pronounced and the phase function remains linear for small observation angles (Buie et al., 1997). Approximation of solar phase angle law by linear function eliminates the necessity to choose the surface reflection law, however such analysis can be performed in future, especially considering new data, obtained by New Horizons.

Second multiplier in the Eq. (2) represents the distortion of the observed image, caused by atmospheric fluctuations. Adaptive optics of novel ground-based telescopes dramatically reduces this negative effect, however atmospheric perturbations significantly complicate the observations on mid-sized telescopes without adaptive systems. In order to take distortion into account we used relatively simple but practical approach, based on approximation of visible blurriness by Gaussian function (Devyatkin and Slesarenko, 2014). For this case Eq. (1) takes form

$$L(x, y, t) = L_0(t) * \frac{1}{2\pi\sigma^2} \exp\left(-\frac{x^2 + y^2}{2\sigma^2}\right), \tag{2}$$

where σ – the variable, which characterize the "blurriness" of the image. Basing on our previous works (Devyatkin and Slesarenko, 2014; Kulish et al., 2009a, 2009b), we used $\sigma = 4''$ for observations, performed on MTM-500M and ZA-320M. This value exceeds the value, presented earlier (Kulish et al., 2009a, 2009b) due to high zenith angle of Pluto–Charon system. Basically, the larger value of σ corresponds to more distorted image, and this value increases with increase of zenith angle due to more prolonged light path through the atmosphere.

The barycenter of n-body system can be easily calculated from the relations between the components masses. The barycenter of the Pluto–Charon system lays on the straight line connecting components' centers on the distance form Plutoб which can be calculated by means of the following formula:

$$R_1 = \frac{Rm_2}{m_1 + m_2}, \tag{3}$$

where R – the distance between Pluto and Charon centers, m_1 and m_2 – masses of Pluto and Charon respectively (Tholen et al., 2008).

According to geometrical, photometrical and physical characteristics of the system (Buie et al., 1997; Cheng et al., 2014), the simulated frames for the different positional angles of Charon were obtained by means of described above approach. Fig. 1 shows real and simulated frames of the Pluto–Charon system for specific observation of 27th March 2003. The photocenter of the system corresponds to the centroid of the simulated frame, which can be