A Giant Step: from Milli- to Micro-arcsecond Astrometry
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CCD astrometric observations of faint satellites and update of their orbits†

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Abstract. This paper reports on our observing campaign of faint satellites performed at the National Time Service Center and Sheshan station of SHAO from 1994 up to today. In the past few years due to benefit from using a large size CCD and the publication of the modern catalogues (UCAC2), a series of observations of faint satellites were obtained by us. Moreover the work of improving the orbit of Phoebe via numerical fit to the observations over a century is also presented.

Keywords. astrometry, solar system: general, planets and satellites: general, ephemerides

1. Introduction

Motivated by the space achievement, in recent years many astronomers have focused their attention on the faint satellites. As part of our ongoing program observing the planetary satellites in successful implement since 1994, we has been carrying out an observing campaign for some faint satellites in last decade. These satellites having magnitude more than 12 are quite faint, the astrometric observations of which are very difficult to make. In our observing program included are Mimas and Phoebe of Saturn, Miranda of Uranus, Triton and Nereid of Neptune.

For these satellites only few astrometric observations were obtained over nearly one century in the past since their discovery mainly due to that the objects are too faint to observe. It results that the accuracy of the existing theoretical models and the ephemeredes are decreasing, the need to improve the ephemeredes urges continually developing new astrometric observations for them.

2. Astrometric calibration

Before 2002 our observations were made using a 1.56m reflector with long focal distance (15.6 m) and a CCD detector of small size. From the instrumental characteristics one gets very small fields. Furthermore the previous star catalogs have a too low density, in the small fields of view no many catalogue stars can be found, so it is incapable to define precisely a known reference system. In this case calibration of CCD is more problematic.

The classical procedure in overcoming this difficulty consists in the construction of a secondary astrometric catalogue of faint stars in the neighborhood of the satellites, however it is obviously inconvenient. Accordingly, the calibration of CCD device was

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made usually using some special methods, for example, in reducing Saturnian satellite system the so-called 'bright moon method' was employed by us. This method relies on positions predicted from pre-existing ephemeredes, in which positions of the bright satellites were used to define a known reference system in every frame.

However, after 2002, we had the opportunity to benefit from two advances in technique: a new large size CCD chip (2048×2048) was used to replace the original one; another important advance should be attributed to publishing the high dense and accurate catalogue UCAC2. Generally about 15-20 UCAC2 reference stars are available for each CCD frame, thus it is enough to allow us to make the classical astrometric reduction directly. For more accurate measurement the typical 6 constants model of plate reduction was selected according to the procedure previously described by Tang (2002).

3. Observation of faint inner satellites

In observing two types of faint satellite, the different difficult might be encountered, for the inner satellites closing to a bright primary, the satellites are embedded in the primary's halo light. Thus in the frames the measured center of image shifts towards the planet's center. The use of CCD provides us possibility to perform the observing faint satellites, which was not possible earlier.

Many authors have presented their methods to minimize the systematic effects of gradients in the background near the planet on the satellite's measured position; all of them made the attempts of using a polynomials surface of degree one or two to fit the inclined sky background. Yan (2007) got a judgment that third degree polynomial is a most judicious choice and is enough to reduce the residuals after a detailed analysis via a numerical simulation as the real data.

In our program observing faint inner satellites included are Saturnian Mimas (mag 12.9) and Uranian Miranda(mag 16.3). Because of the unavoidable effect from halo light in the proximity of the primary, centering of the satellite image is generally difficult to measure. The 44 measurements of the positions of Mimas during 1997–2000 and the 83 measurements for Miranda during 1995–1997 were obtained.

In reduction of the satellite we have successfully applied the 'brighter moon method' to the calibration of the CCD chip (Shen et al. 2002; Qiao *et al.*, 2004), four better-known satellites were used as calibration satellites. The analytical theories TASS1.7 and GUST86 were used for theoretical computation. The calculations exhibit that for Mimas and Miranda the poor residuals are as large up to $0\farcs1$.

4. Observation of faint outer satellites

For the outer satellites in lager distance to the primary, the main difficulty consists in that no planet or major satellites with the satellite are present in the same field of view even when using CCD of large size; the satellites appear as an isolated object. Thus, the differential measurement relative to the major satellites of Saturn or reference satellite is very unlikely. As a consequence, the previous methods of astrometric reduction used for the planet's inner satellites cannot be performed. The following faint outer satellites have been studied.

(1) **Phoebe**. Phoebe is a most distant known outer satellite of Saturn (more than 12 million km). In each CCD frame this satellite appears as an isolated object with extremely faint visual magnitude (mag 16.45).

At 6 nights in December 2003 and at 3 nights in March 2004 a total of 115 frames were obtained. In this work, because of the use of a CCD detector with a wider field,

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the object to be measured and a much lager number of background stars are available in the field of view. The 'CENTER' command was used in batch mode to determine accurately the positions of all the targets, furthermore the Gaussian method, which is a 2-dimensional Gaussian function, including a term to represent the background level was used; the rough sky background bias was estimated and removed from each image. For the detailed procedure the reader can be referred to the paper Qiao *et al.* (2006).

In 2005, we completed a re-determined Phoebe's orbits (Shen *et al.*, 2005). In order to best determine Phoebe's orbit, it is necessary that the observations cover the longest time span as possible, in this reduction we used the 686 Earth-based astrometric observations available from 1905 to 2004, including the 101 new CCD observations from Qiao and Tang (2006) and 57 observations from Peng (2004).

The numerical integration was calculated using the 12th-order Runge-Kutta-Nystrom formula of Brankin. For Phoebe, the overwhelming perturbation is due to the Sun. The other perturbation induced from Jupiter and Uranus were computed using their positions derived from the JPL planetary ephemeris DE406. The perturbation from Titan is included as sole perturbing satellite.

(2) **Triton**. Before our observing Triton (mag 13.47), only less than 400 positions have an accuracy of better than $0''.15$. Qiao reported that he and his colleagues took the 943 astrometric observations of Triton in the period of 1996–2006 (Qiao *et al.*, 2007).

A two-dimensional Gaussian to each image and a third-degree polynomial were considered by Yan (2007) for simulating sky background. The observed positions of Triton are compared with theoretical positions generated by the JPL and IMCCE ephemeredes respectively. The residuals of observations are about $0''.04$.

(3) **Nereid**. Nereid is a very faint satellite of Neptune (mag 18.7), very poorly observed since its discovery. In 2006 we started observing campaign of Nereid using the 2.16m telescopes in National Astronomical Observatories (including original Beijing Astronomical Observatory, Yunan Astronomical Observatory and institute of astronomical instruments), with which the 71 observations have been taken. At present the observations have been in reduction. For permitting to record a faint image of this satellite long exposure time (more than 20 min) is usually needed.

5. Summary

We have presented a report on our astrometric campaign on faint satellites spanning the period from 1994 to 2007 as part of our ongoing observing program of the planetary satellites, which was initiated at Sheshan station in 1994. In the past 15 years a large number of highly accurate observations have been obtained. We have shown that the observations are highly accurate and significant for orbit determination of faint, poorly observed satellites.

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