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**ABSTRACT**

Astrometric positions of the Neptunian Satellite Triton are given for the opposition of Neptune for the years 1996, 2003, 2005 and 2006. The 943 observed positions were obtained at the Cassegrain focus of a 156 cm reflector. In our reduction, the up-to-date catalogue of stars UCAC2 (Zacharias et al. 2004), was chosen to ensure a proper astrometric calibration. Our observed positions are compared to theoretical positions provided from JPL and IMCCE ephemerides. The observed minus calculated residuals have standard deviations of the order of 0.04".

**Key words:** planets and satellites - satellites of Neptune - astrometry

## 1 INTRODUCTION

Triton is the largest moon of Neptune, with a diameter of 2,700 kilometers (1,680 miles). It was discovered by William Lassell, a British astronomer, on October 10, 1846 scarcely a month after Neptune was also discovered.

With a successful passage of the Voyager 2 spacecraft through the Neptunian planetary system in 1989, it was revealed that Triton is a most peculiar satellite in the solar system because of the great differences between its two sides arisen from synchronously rotating around Neptune. This remarkable feature attracts more attention from scientists to this satellite and the new campaign of observation is developing for improving accuracy of its ephemeris. In recent years, several series of new valuable CCD observations have been published by Veiga et al. 1996, Veiga & Martins (1996) and by Veiga & Martins (1998).

As the continuation of our systematic program of astrometric observations of natural satellites initiated in 1985, we successfully developed in the recent years the campaign of observations of Phoebe (Qiao et al. 2006). A similar campaign for Triton was carried out and its results are presented here. So, in this paper, we report the 943 observed positions

of Triton obtained in the period from 1996 to 2006 with our CCD camera.

This paper is organized as follows: in Sect. 2 we describe the observations and reduction procedures; in Sect. 3 we compare our results with theoretical positions calculated from JPL and IMCCE ephemeris. Finally a conclusion is presented in Sect. 4.

## 2 OBSERVATIONS, MEASUREMENT AND DATA REDUCTION

### 2.1 New observations

The observations presented here were attained with the 156 cm telescope at the Sheshan station (Longitude= $121°11'03''.3E$, Latitude= $31°05'46''.1N$, Altitude= 97 meters) near the Shanghai Astronomical Observatory. For full details concerning the CCD detector and reflector the reader can be referred to Qian & Tao (2003).

For the first observations in 1996, we used a cooled CCD camera which is an array of $1024 \times 1024$ squares pixels, the size of each pixel being 0.019 mm which corresponds to 0".25 on the sky. The field of view of the telescope was 4'17". After 2002, this chip was replaced by a new liquid-nitrogen-cooled CCD of $2112 \times 2048$ square pixels with 0.024 mm for each pixel. This large CCD chip corresponds to a wide field of about $11' \times 11'$.

**Table 1.** Extract of the list of our observed positions of Triton available at the CDS via anonymous ftp or on request by email. These positions are topocentric and given in the ICRF J2000 system.

| Year | M | Day(UTC) | $\alpha$ | $\delta$ |
|------|------|----------|-----------|-----------|
| 2006 | 09 | 18.47223 | 21 19 32.928 | -15 49 47.85 |
| 2006 | 09 | 18.47778 | 21 19 32.904 | -15 49 47.98 |
| 2006 | 09 | 18.48194 | 21 19 32.896 | -15 49 48.16 |
| 2006 | 09 | 18.48508 | 21 19 32.877 | -15 49 48.28 |
| 2006 | 09 | 18.49167 | 21 19 32.850 | -15 49 48.49 |
| 2006 | 09 | 18.49514 | 21 19 32.838 | -15 49 48.62 |
| 2006 | 09 | 18.49722 | 21 19 32.821 | -15 49 48.60 |
| 2006 | 09 | 18.49932 | 21 19 32.820 | -15 49 48.69 |
| 2006 | 09 | 18.50347 | 21 19 32.802 | -15 49 48.84 |
| 2006 | 09 | 18.50625 | 21 19 32.791 | -15 49 48.92 |
| 2006 | 09 | 18.50833 | 21 19 32.782 | -15 49 48.99 |
| 2006 | 09 | 18.51250 | 21 19 32.762 | -15 49 49.08 |

In Fig. 1, two typical CCD frames on two different nights with Triton are presented to exemplify the observing and measurement procedures. In the frames, the UCAC2 reference stars, which are marked by a small circle, are used for the calibrating reduction. Triton is indicated by an arrowhead and its motion relative to Neptune is clearly seen with the aid of comparison between the two frames. For all observations, no filter was used and the exposure time varied from 10 to 120 seconds, depending on the meteorological conditions.

The flat field images were taken at dusk and dawn. The bias is taken at the beginning of the observation and the end. The dark field images were taken in the end. The range of seeing of Sheshan Station is 1".1-1".9, typically 1".5. The mean value of the FWHM of images is about 1".7, which is bigger than seeing because of the guide error and focus error.

As in our previous works, the centering of star and satellite images were processed by using the IRAF software package, similar as that in our previous measuring. We used the CENTER algorithm which applies a bi-dimensional Gaussian to every image and considers a second degree polynomial for the sky background. The centering error of Triton is about 0".02.

In the present work, our new observations spanning the period from 1996 to 2006 are included. As the orbiting period of Triton is only about 5.8 days, the interval of time of our observations was high enough to cover the whole orbit of this satellite, as it can be seen on Fig. 2.

## 2.2   The astrometric calibration with the UCAC2 catalog

Since the publication of the high density and high accurate star catalogue UCAC2 (Zacharias et al. 2004), it became possible to make the astrometric calibration of the CCD frame directly without using secondary catalog or so called the 'brighter moon calibration' (Shen et al. 2001). In this paper, we have chosen the UCAC2 to calibrate our CCD fields, as we did in our previous work (Qiao et al. 2006). Because of the large number of reference stars provided by this catalogue, it is ensured that about 10-30 UCAC2 reference
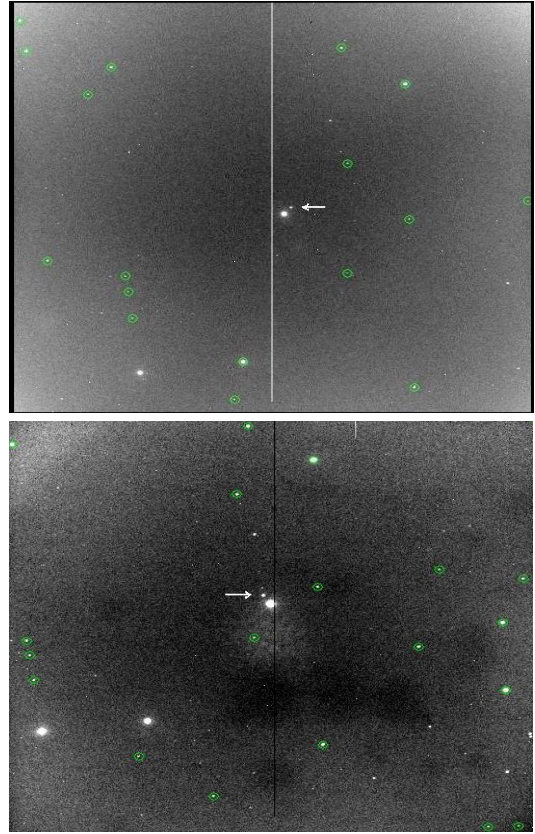


**Figure 1.** CCD frames observed: (top)- at $15^h03^m00^s$ of 24/08/2006 UTC; (bottom)- at $17^h36^m01^s$ of 25/08/2006 UTC. The exposure time is $1^{mn}$, the CCD size is $2112 \times 2048$ square pixels. Triton is shown by the arrowhead near Neptune.
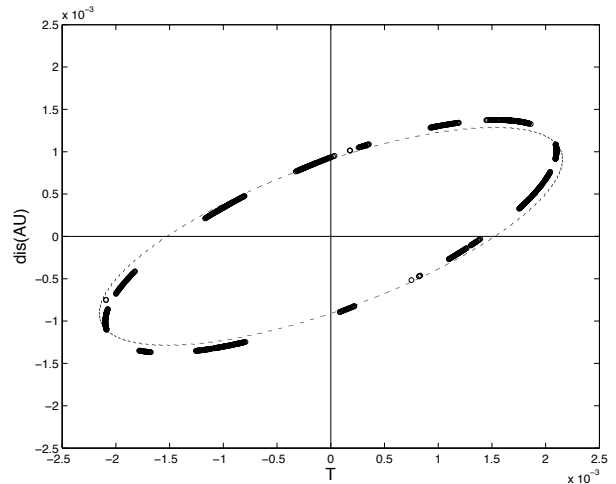


**Figure 2.** The distribution of the observations in Triton's orbit.

stars are available for each of our CCD images. This is quite enough for allowing a classical astrometric calibration using the 6 constants model of frame, as described by Tang et al. (2002).

In Table 1, we give an extract of the list of the observed positions of Triton. All data are available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr.
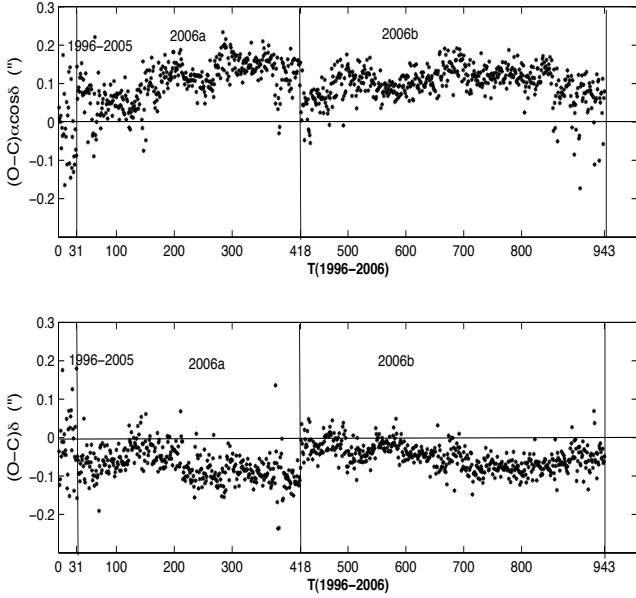
**Figure 3.** Plots of residuals in right ascension and declination of the absolute positions of Triton, derived from the comparison of our all observations to the JPL ephemeris vs. time T(1996 - 2006)
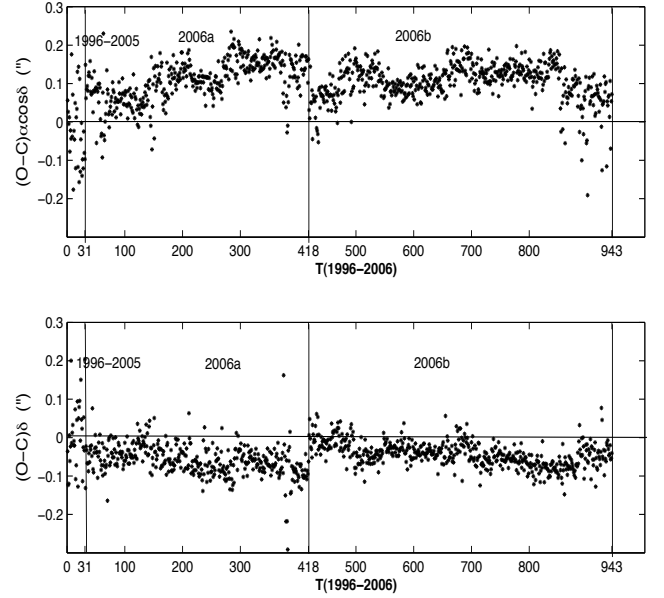


**Figure 4.** Plots of residuals in right ascension and declination of the absolute positions of Triton, derived from the comparison of our all observations to the IMCCE ephemeris vs. time T(1996 - 2006)

The data are presented in the following form: the first three columns gives the year, month and decimal day in UTC, corresponding to the mean instant of the observation. In the next columns we list the right ascension $\alpha$ and the declination $\delta$ in arcseconds of Triton. The reference system is defined by the mean equator and equinox J2000 in the ICRF system.

## 3 COMPARISON WITH THE THEORETICAL POSITIONS

### 3.1 The two ephemerides used for comparison with observations

The observed positions of Triton are compared with theoretical positions of the satellite generated by the two ephemerides available now on the web: JPL NEP016 and IMCCE.

The JPL NEP016 ephemeris (Jacobson, 2004) can be directly found on the JPL's Horizons system. It is derived from the theory developed by Jacobson et al. (1991) adjusted to earth-based and Voyager observations made before 1989. Triton's absolute positions on this site are derived from the newest planetary ephemeris DE405 by Standish (1998).

The theoretical positions from the other ephemeris IMCCE can be obtained on the saimirror web site of the IMCCE. They are derived from the same theory developed by Jacobson et al. (1991) and the same DE405 planetary ephemeris for Neptune.

Our complete observations are divided into 3 groups: 1996-2005(11/8/1996, 24/8/2003, 5/9/2005), 2006a(18-25/8/2006) and 2006b(18-27/9/2006). From the comparison of our observations to the theoretical positions provided by the two ephemerides above, we have evaluated the respective mean residuals $\mu$ and standard deviations $\sigma$ for the three sets of data. Their values are listed in Table 2. Moreover, Fig. 3

**Table 2.** Mean residuals $\mu('')$ and standard deviations to the mean $\sigma('')$ of the absolute positions of Triton for the 3 sets of observations: 1996-2005, 2006a and 2006b. These observations are compared to both of the ephemeris available on the respective JPL and IMME web sites. $N_u$ is the number of observed positions for each set of observations.

| Set | | $N_u$ | JPL | | IMCCE | |
|-----|------|-------|-------|-------|-------|-------|
| | | | $\sigma$ | $\mu$ | $\sigma$ | $\mu$ |
| 1996 | $\Delta\alpha\cos\delta$ | 31 | 0.090 | -0.024 | 0.085 | -0.020 |
| -2005 | $\Delta\delta$ | 31 | 0.086 | -0.008 | 0.082 | -0.010 |
| 2006a | $\Delta\alpha\cos\delta$ | 387 | 0.055 | 0.109 | 0.055 | 0.106 |
| | $\Delta\delta$ | 387 | 0.041 | -0.058 | 0.045 | -0.073 |
| 2006b | $\Delta\alpha\cos\delta$ | 525 | 0.050 | 0.102 | 0.046 | 0.099 |
| | $\Delta\delta$ | 525 | 0.033 | -0.043 | 0.034 | -0.049 |

and Fig. 4 provide plotting of the residuals (O-C) versus the 3 sets of observations, for the two ephemerides.

### 3.2 Discussion

The comparison of the observations with the JPL and IMCCE ephemerides in section above first shows that no noticeable difference is exhibited between the residuals derived from both of these ephemerides, presented in Table 2 and displayed in Fig.3 and Fig.4. This means that the positions of Triton computed by these two ephemerides are quite close. This is not surprising as we mentioned above that they both are derived from the same theory of Triton (Jacobson et al, 1991) and the same planetary ephemeris DE 405. Then, the analysis of the standard deviations of residuals given in Table 2 shows the high accuracy of our observations, with

values close to 0".04 for both of the 2006 observation sets including the most important part of all our observed positions (912 out of 943). The first set of observations presents some higher residuals, mainly due to weather conditions, particularly bad during the 1996 and 2003 missions. But they represent a minor part of the whole data (31 positions out of 943).

Also, Fig. 3 and Fig. 4 show that for the two missions in 2006 (2006a and 2006b) the mean residuals ($\mu$) in right ascension clearly present a positive offset, close to 0".1 But in declination the offset appears to be slightly negative, with mean residuals of about -0".05. This second offset is less significant as its value is very close to the accuracy of the observations. These offsets could be induced by measurement and reduction factors, as for instance by a possible imperfect refraction correction. But we have evaluated that such high offsets cannot be derived from a refraction correction as the elevation of Triton generally is larger than 30 degrees. So, it appears that these offsets, mainly affecting the right ascension of our most recent observations, could emphasize a slight loss in the accuracy of the ephemerides of Triton which were adjusted to observations older than ours.

## 4    CONCLUSION

In this paper we have presented 943 CCD astrometric positions of Triton measured on the all CCD frames taken over the 1996-2006 period. We have used the same telescope and the same methods of reduction as in all our earlier works (Qiao et al., 1999; Shen et al., 2001 and Qiao et al., 2004). But the CCD chip with a large size of 2112x2048 pixels used in the present work only was used in our next work (Qiao et al. 2006). Our observations are distributed over 20 nights during the four missions from 1996 to 2006. The UCAC2 catalog stars are used for the astrometric calibration. The comparison of our observations with the JPL and IMCCE ephemerides has emphasized their high accuracy, with residuals of about 0".04.

Veiga et al. (1996) mentioned that among the 2000 observed positions of Triton published since its discovery, only less than 400 positions have an accuracy better than 0".15. So, we can expect that the 943 observed positions presented in this paper will appear quite significant and valuable in any future determination of the parameters of Triton's orbit.

We prepare now the re-determination of the orbit of this satellite by using the more important amount of observed data available now, including the numerous and high quality observations presented in the present paper.

## ACKNOWLEDGMENTS

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