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New astrometric observations of Triton in 2007–2009[★]

R. C. Qiao,^{1†} H. Y. Zhang,^{1,2} G. Dourneau,^{3,4} Y. Yu,⁵ D. Yan,^{1,2} K. X. Shen,¹
X. Cheng,^{1,2} X. J. Xi,^{1,2} X. Y. Hu⁶ and S. H. Wang⁵

¹National Time Service Center (NTSC), Chinese Academy of Sciences, Lintong, Shaanxi 710600, China

²University of the Chinese Academy of Sciences, Beijing 100039, China

³Univ. Bordeaux, LAB, UMR 5804, F-33270 Floirac, France

⁴CNRS, LAB, UMR 5804, F-33270 Floirac, France

⁵Shanghai astronomical Observatory (SHAO), Chinese Academy of Sciences, Shanghai 200030, China

⁶Max-Planck-Institut für Sonnensystemforschung, Max-Planck-Strasse 2, D-37191 Katlenburg-Lindau, Germany

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ABSTRACT

Astrometric positions of the Neptunian satellite Triton with a visual magnitude of 13.5 were obtained during three successive oppositions in 2007, 2008 and 2009. A total of 1095 new observed positions of Triton were collected during 46 nights of observations, involving eight missions and three telescopes. We compared our observations to the best ephemerides of Triton available now. This comparison has shown that our observations present a high level of accuracy as they provide standard deviations of residuals hardly higher than 50 mas and mean residuals lower than 30 mas, corresponding to about only 500 km in the position of the very distant satellite Triton. Moreover, we have compared most of the different planetary ephemerides of Neptune available now as well as two recent orbit models of Triton. These new comparisons have clearly shown the differences between all of these ephemerides which can be significant and that are presented in this work.

Key words: astrometry – planets and satellites: general.

1 INTRODUCTION

The giant planets Jupiter, Saturn, Uranus and Neptune with their respective satellites form some micro-solar systems in which various gravitational, orbital and physical problems of interest are similar. These small solar systems constitute several natural laboratories for the study of the formation and evolution of the Solar system. Meantime, the researches of natural satellites motion can greatly facilitate the improvement of ephemeris for major planets. We initiated an astrometric observing programme of natural satellites in 1985. Some results of our observations (Qiao et al. 2007, 2008, 2011, 2013) have been already used to develop new orbits for satellites, such as the eight main satellites of Saturn (Harper et al. 1988; Dourneau 1993; Harper & Taylor 1993), Phoebe the ninth satellite of Saturn (Shen et al. 2005; Emelyanov 2007; Desmars et al. 2013), the major satellites of Uranus (Emelyanov & Nikonchuk 2013) and Triton the main satellite of Neptune (Jacobson 2009; Zhang et al. 2014).

Triton, the largest satellite of Neptune, was discovered by the British astronomer William Lassell using telescope on 1846

October 10. Triton is slightly smaller than Europa and has an unusual retrograde and nearly circular orbit. Its density, brightness and albedo indicate that it is composed mostly of water ice with rock. Spectral observations show that ices of nitrogen and methane are important on the surfaces (Christiansen & Hamblin 2007). Its retrograde orbit and high inclination indicate that Triton may have been captured by Neptune being originally in a heliocentric orbit around the sun (Agnor & Hamilton 2006). Over the years, attracted to these remarkable features of Triton, many scientists devote themselves to advocating and developing observing campaigns for Triton in order to improve the accuracy of its ephemeris. In recent years, several series of new valuable CCD observations have been published (Veiga et al. 1996; Veiga & Vieira 1996, 1998; Vieira et al. 2004; Chanturia & Kisseleva 2006; Qiao et al. 2007). As a continuation of our previous observing campaign of 1996–2006 (Qiao et al. 2007), we present in this paper 1095 new observed positions of Triton which were obtained by using three different telescopes at two different stations during the period 2007–2009, spreading over 46 nights involving eight missions.

The three used telescopes are the 1.56 m astrometric reflector at the Sheshan station of the Shanghai Astronomical Observatory (SHAO, N31°09′6″, E121°18′4″, H97 m, code 337) near Shanghai, and the two respective reflectors with 1.00 m and 2.16 m diameter at the Xinglong station of the National Astronomical Observatory (NAO, N40° 39′6″, E117° 57′7″, H940 m, code 327) near Beijing.

[★]The data are available in electronic form by Email. As Supplementary Material to the online version of the paper on Blackwell Synergy, at the CDS via Anonymous FTP to cdsarc.u-stasbg.fr or via <http://cdsweb.u-strasbg.fr/Abstract.html>.

†E-mail: rcqiao@ntsc.ac.cn

All the three telescopes were equipped with cooled CCD cameras presenting an array of 2112×2048 pixels for the 1.56 m telescope, 1340×1300 pixels for the 1.00 m telescope and 2080×2048 pixels for the 2.16 m telescope.

This paper is organized as follows. The observations and reduction procedures are described in Section 2. In Section 3, we evaluate the accuracy of our observations of Triton from their comparison to the best available ephemerides of this satellite provided by Jacobson (2009) and by Zhang et al. (2014), associated with the planetary ephemeris DE431 for Neptune. Also in Section 3, we compare the two orbit models of Triton by Jacobson (2009) and by Zhang et al. (2014). In Section 4, we compare most of the ephemerides of Neptune available now, so that 10 different planetary ephemerides are analysed in this work. Our determination of the differences between each of these ephemerides are reported here. Finally, in Section 5, we draw some conclusions.

2 OBSERVATIONS, MEASUREMENT AND DATA REDUCTION

The 1.56 m telescope, equipped with a large liquid-nitrogen-cooled CCD and located at the Sheshan Station, was used in the five missions made in 2007 August and September, 2008 August and September and 2009 August. In these five missions, we always used the binning mode in which the charges of 2×2 pixels can be read out in the process, so that we can achieve a higher SNR (signal-to-noise ratio) during the period of observation. Consequently, the pixel number becomes 1056×1024 pixels, so that the size of each pixel now is $48 \mu\text{m}$. This large CCD chip corresponds to a wide field of about $11.2 \text{ arcmin} \times 10.8 \text{ arcmin}$. The exposure time varied from 10 to 80 s, depending on the meteorological conditions.

In the observing missions of 2007 August and September, we also used the 1.00 m telescope at the Xinglong Station, and the exposure time varied from 10 to 120 s. In the mission undertaken in 2007 August, the 2.16 m telescope was also used, and the exposure time varied from 10 to 100 s.

For all our observations from 2007 to 2009, no filter was used and flat-field images were taken at dusk and dawn. In addition, bias and dark images were obtained at the beginning and at the end of the observations. For more instrumental details concerning the CCD detectors and the reflectors, see Table 1.

In our previous measurement process of the CCD frames, we used the IRAF or the ASTROMETRICA software packages. In this paper, the reduction program recently developed by Yan et al. (2014) was used for the measurement and the astrometric reduction of the CCD frames. By configuring the correct parameters corresponding to the observing system (including telescope and CCD) and the feature of the images, the software is specially designed for processing natural

Table 2. An extract of the list of the observed topocentric equatorial coordinates of Triton, given in the mean equator and equinox of J2000.0. The full table is available in the electronic version of this article.

Year	Month	Day(UTC)	α (h m s)	δ (d m s)	Site
2008	09	10.520 8411	21 38 06.137 29	-14 29 35.585	337
2008	09	10.527 7888	21 38 06.100 13	-14 29 35.844	337
2008	09	10.529 1829	21 38 06.094 18	-14 29 35.915	337
2008	09	10.531 2631	21 38 06.085 82	-14 29 36.026	337
2008	09	10.533 3440	21 38 06.077 48	-14 29 36.088	337
...

satellites images and presents the advantage of providing the batch function.

It rejected the false star images (bad pixels and other false star images) according to the two constraints which are the minority value of pixels' number for a real star and the minority SNR value. The centring of star images was fixed on by using the method of the centre of gravity. The identification of the stars of the catalogue on the CCD frames was fulfilled by the method of triangle matching.

We have used the UCAC2 catalogue (Zacharias et al. 2004) in preference to the more recent UCAC3 catalogue (Zacharias et al. 2010). Although UCAC3 is a higher density catalogue than UCAC2, it can be affected by some systematic zonal errors which have recently been detected by several authors as Roeser, Demleitner & Schilbach (2010), Krone-Martins et al. (2010) and Qiao et al. (2011). Anyway, the UCAC2 CCD astrophot catalogue (Zacharias et al. 2004) remains one of the most accurate high-density astrometric catalogues currently available now. It covers a wide range of magnitude from about 9 to 16, and provides positions and proper motions of more than 48 million stars referred to the Earth mean equator and equinox of the J2000.0 system (ICRF). Zacharias et al. (2004) claimed that the positional accuracy of stars in UCAC2 is between 15 and 70 mas, depending on the magnitude.

Moreover, the CCD chips mounted on the three used telescopes have wide field slightly greater than $10.0 \text{ arcmin} \times 10.0 \text{ arcmin}$, in which a large number of catalogued stars in UCAC2, generally from 20 to 40, can be ensured to be present on each of all our CCD images. Consequently, the UCAC2 catalogue appeared quite suitable to be used in this work as it provides a sufficient number of reference stars to ensure a reliable astrometric reduction.

Table 2 presents an extract of the list of the observed positions of Triton supplied by this paper. The first three columns of Table 2 are the year, month and decimal day in UTC of the middle time of each CCD frame. We also list Triton's right ascension, expressed in hour, minute and second, and declination, expressed in degree, arcminute and arcsecond in the next two columns. The last column supplies the international site codes of the observations. These equatorial coordinates are topocentric and given in the mean equator and equinox of

Table 1. Specifications of the three telescopes and CCD chips used for the observations of Triton.

Telescope	A	B	C
Diameter of primary mirror	156 cm	100 cm	216 cm
Focal length	15 600 mm	7800 mm	10 000 mm
Size of CCD array (pixels)	2112×2048	1340×1300	2080×2048
Size of pixel	$24 \mu\text{m}$	$20 \mu\text{m}$	$15 \mu\text{m}$
Angular extent per pixel	0.32 arcsec	0.53 arcsec	0.31 arcsec
Field of view	$11.2 \text{ arcmin} \times 10.8 \text{ arcmin}$	$11.8 \text{ arcmin} \times 11.4 \text{ arcmin}$	$10.7 \text{ arcmin} \times 10.5 \text{ arcmin}$
Bandpass of CCD (nm)	300–1100	200–1100	300–1000

J2000.0. The complete data can be obtained upon request via e-mail, as Supporting Information in the online version of this article, or on the website of the CDS at the following address: <http://cdsweb.u-strasbg.fr/Abstract.html>, or via anonymous FTP to cdsarc.u-strasbg.fr. In addition, all our observations are being available on the Natural Satellite Data Center (NSDC) of the IMCCE at the address: http://www.imcce.fr/hosted_sites/saimirror/bnepomae.htm (Arlot & Emelyanov 2009).

3 COMPARISON OF OUR OBSERVATIONS TO THE EPHEMERIDES OF TRITON

In order to check and analyse our observations, we first have compared them to one of the best ephemerides available now. This ephemeris is derived from the orbit of Triton developed by Jacobson (2009) associated with the DE431 planetary ephemeris of Neptune. The theoretical positions of Triton were obtained from the MULTISAT server of the IMCCE (Emelyanov & Arlot 2008). In order to eliminate the aberrant observations, we have used a rejection level of 0.2 arcsec. The residuals have been computed for each of the eight missions and for all the observations together. The mean residuals and the standard deviations of residuals are given in Table 3. We can observe that the standard deviations obtained for all our observations are hardly higher than 50 mas, which is a reliable evaluation of their accuracy. Moreover, the corresponding mean residuals are smaller, with less than 30 mas, showing that our observations and the used ephemerides present a very high accuracy, corresponding to about only 500 km in the position of the very distant satellite Triton. Also from Table 3, the residuals obtained for each used instrument show that the 1.56 m telescope provided the most accurate and homogeneous observations, with residuals lower than 50 mas. As most of our observations, nearly 90 per cent, were made with this instrument, it had a positive effect on the high accuracy of all our observations presented here. The 1.00 m telescope is the smallest that we have used in this campaign. So, it is not surprising that it provided the higher residuals, although remaining very low, from only 30 to 130 mas. But a few numbers of observations, less than 10 per cent, were made with this instrument. At last, the 2.16 m telescope, the largest that we have used, provided intermediate residuals. The accuracy of the observations made during this specific mission would certainly have been better with more favourable weather conditions. Also, in Fig. 1, we have plotted the residuals versus time for each of the eight missions from 2007 to 2009. Fig. 1 visualizes and confirms the different levels of accuracy

of each used instrument that we have evaluated and discussed just above from the values of Table 3.

Table 3 also provides the residuals derived from the very recent ephemeris of Triton developed by Zhang et al. (2014). These residuals appear to be quite similar to those derived from Jacobson (2009), within 1 mas for the mean residuals, corresponding to only 20 km in the position of Triton. This shows that both of the two orbits by Jacobson (2009) and by Zhang et al. (2014) can be considered as equivalent for the recent period of our observations from 2007 to 2009. This can be explained because each of the two orbits present some specific advantages. On one hand, Zhang et al. (2014) have used more recent CCD observations than Jacobson (2009). But on the other hand, Jacobson (2009) is the only one to have used the positions of Triton derived from the Voyager 2 spacecraft mission. Moreover, the low residuals obtained by using both of these two ephemerides of Triton emphasize their very high shared accuracy.

4 COMPARISON OF THE DIFFERENT EPHEMERIDES OF NEPTUNE

We have compared our observations by using most of the ephemerides of Neptune available now, in order to compare them and to evaluate their respective reliability. For this purpose, we have considered the different planetary ephemerides successively developed at JPL as DE200 (Standish 1990), DE405, DE406, DE421 and DE431 and at IMCCE as VSOP87 (Bretagnon & Franco 1988), INPOP6, INPOP8 and INPOP10 (Fienga et al. 2008, 2009, 2011). We have also considered the ephemeris EPM2011m developed by Pitjeva et al. (2005). Finally, we have considered a total of 10 different ephemerides of Neptune to be compared now. For the satellite Triton, we have used the two orbits developed by Jacobson (2009) and by Zhang et al. (2014).

All the theoretical positions of Triton to be compared to our observations have been obtained from the MULTISAT server of the IMCCE (Emelyanov & Arlot 2008), which presents the specific advantage of providing all the different ephemerides of Neptune and Triton listed just above. The values of the residuals derived from the comparisons of all our observations to the different ephemerides of Neptune and Triton are presented in Table 4.

First of all, the residuals of Table 4 derived from both of the two ephemerides of Triton developed by Jacobson (2009) and by Zhang et al. (2014), appear quite similar, within 1 mas for the mean residuals, whatever the used planetary ephemeris. This confirms the

Table 3. The mean residuals μ (arcsec) and standard deviations σ (arcsec) of the O–C residuals of the comparison between our observations and the theoretical positions from Jacobson (2009) + DE431 and from Zhang et al. (2014) + DE431 are presented here. They are expressed in arcseconds and computed for each mission of observations and for all the observations. N.(d) is the number of observing nights of Triton for each mission or for all observations. N.(Images) is the number of observed positions of Triton for each mission or for all observations.

Telescope	Mission	N.(d)	N.(Images)	Jacobson (2009)+DE431				Zhang et al. (2014)+DE431			
				μ_α (arcsec)	μ_δ (arcsec)	σ_α (arcsec)	σ_δ (arcsec)	μ_α (arcsec)	μ_δ (arcsec)	σ_α (arcsec)	σ_δ (arcsec)
A (1.56 m)	2007 Aug.	8	429	0.043	−0.016	0.041	0.052	0.048	−0.022	0.043	0.056
	2007 Sep.	7	183	0.050	−0.044	0.045	0.051	0.048	−0.037	0.047	0.052
	2008 Aug.	7	109	−0.043	−0.057	0.053	0.051	−0.046	−0.055	0.055	0.050
	2008 Sep.	7	102	−0.018	−0.027	0.064	0.052	−0.025	−0.016	0.067	0.056
	2009 Aug.	4	133	0.041	−0.033	0.054	0.042	0.045	−0.038	0.053	0.043
B (1.00 m)	2007 Aug.	1	19	−0.050	−0.139	0.031	0.038	−0.044	−0.149	0.033	0.039
	2007 Sep.	6	70	0.036	−0.040	0.106	0.103	0.038	−0.042	0.112	0.106
C (2.16 m)	2007 Aug.	6	50	−0.068	0.029	0.095	0.100	−0.072	0.031	0.099	0.103
Total (A+B+C)	8	46	1095	0.023	−0.029	0.067	0.062	0.024	−0.030	0.071	0.065

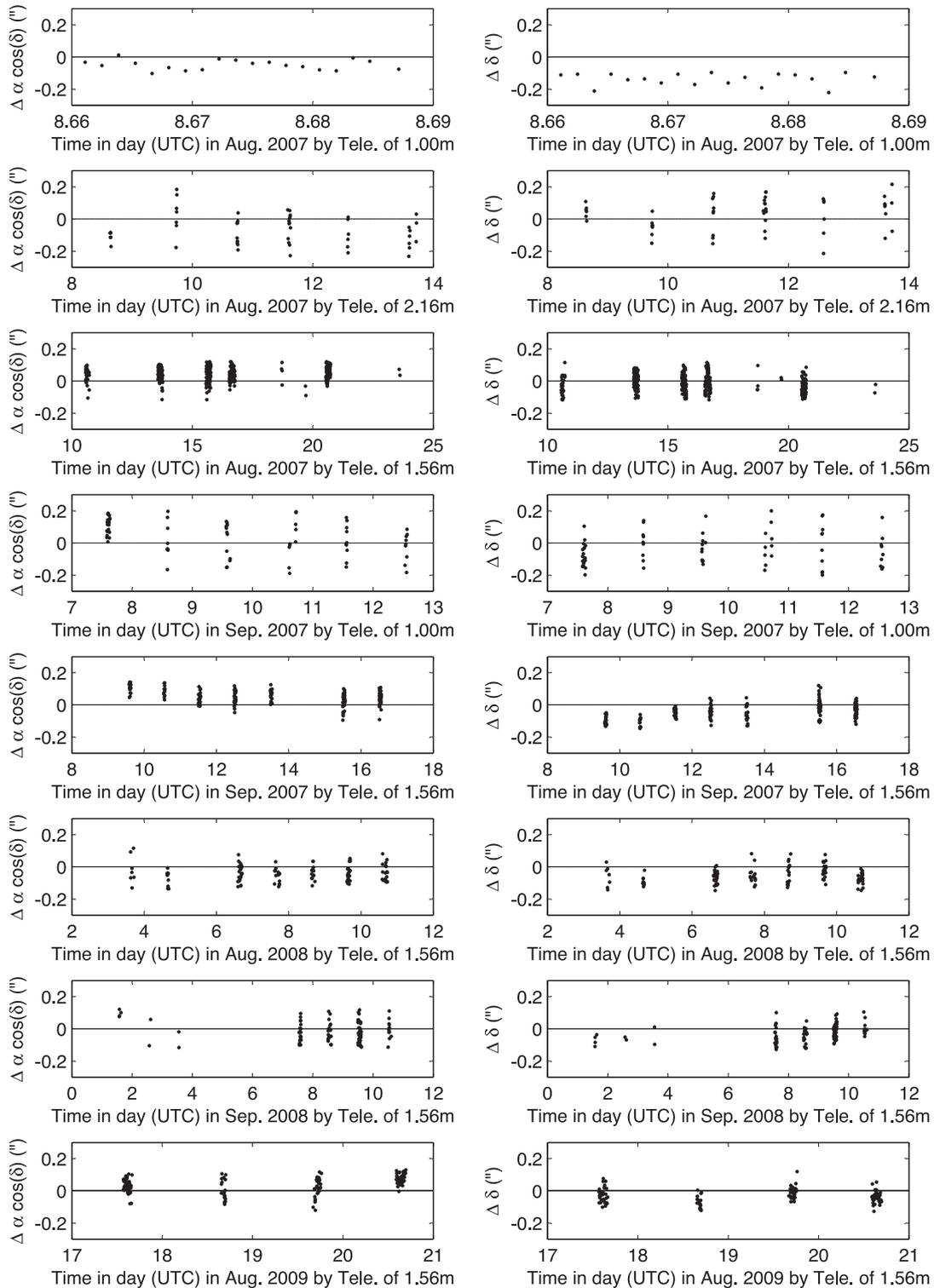


Figure 1. Residuals (O–C) of Triton in 2007–2009 relative to the eight sets of observations, derived from the comparison of all our observations to the Triton orbit model by Jacobson (2009) combined with DE431 planetary ephemerides.

equivalence and the high accuracy of the two Triton orbits that we had already shown just above from the analysis of Table 3.

Afterwards, for each of the two ephemerides of Triton, Table 4 shows that the lowest mean residuals are obtained with DE421, similar to EPM2011m, in right ascension (22 mas) and with INPOP06 in declination (–28 mas). However, these last three ephemerides

do not present the lowest mean residuals in the other equatorial coordinate: INPOP06 in right ascension (33 mas) and DE421, also similar to EPM2011, in declination (–48 mas). Besides, Table 4 shows that DE431 is the only ephemeris providing mean residuals lower than 30 mas in both coordinates (23 mas in right ascension and –29 mas in declination). Consequently, DE431 appears

Table 4. Mean residuals μ (arcsec) and standard deviations σ (arcsec) of the O–C residuals derived from the comparison of our observations to the theoretical positions of Triton successively obtained from 10 different planetary ephemerides of Neptune and from the two orbits of Triton by Jacobson (2009) and by Zhang et al. (2014). The residuals are expressed in arcseconds and computed for all the 1095 observations made in the period 2007–2009.

No.	Planetary ephemerides	Triton model: Jacobson (2009)				Triton model: Zhang et al. (2014)			
		μ_α (arcsec)	μ_δ (arcsec)	σ_α (arcsec)	σ_δ (arcsec)	μ_α (arcsec)	μ_δ (arcsec)	σ_α (arcsec)	σ_δ (arcsec)
1	DE431	0.023	−0.029	0.067	0.062	0.024	−0.030	0.071	0.065
2	DE421	0.022	−0.048	0.070	0.062	0.022	−0.049	0.071	0.065
3	DE405	0.051	−0.076	0.069	0.062	0.051	−0.077	0.070	0.065
4	DE406	0.051	−0.076	0.069	0.062	0.051	−0.077	0.070	0.065
5	DE200	−0.900	−0.390	0.073	0.065	−0.900	−0.391	0.074	0.067
6	INPOP10	0.044	−0.109	0.069	0.063	0.045	−0.110	0.070	0.065
7	INPOP08	0.072	−0.053	0.069	0.062	0.072	−0.054	0.070	0.065
8	INPOP06	0.033	−0.028	0.069	0.062	0.033	−0.029	0.070	0.065
9	EPM2011m	0.022	−0.047	0.070	0.062	0.022	−0.048	0.071	0.065
10	VSOP87	−0.816	−0.361	0.073	0.064	−0.815	−0.362	0.074	0.067

to be the most homogeneous and accurate planetary ephemeris among the 10 different ones analysed here. Then, Table 4 shows a group of ephemerides, including DE405, DE406, INPOP08 and INPOP10, which present intermediate mean residuals from about 50 to 100 mas. Afterwards, it is not surprising that the highest mean residuals of Table 4, from about 400 to 900 mas, are obtained with the two ephemerides DE200 and VSOP87. They are the oldest ones so that they present significant drifts of their theoretical positions for the recent period of our observations, from 2007 to 2009. Oppositely, it was not obvious to expect that INPOP06 would present lower mean residuals than the more recent versions INPOP08 and INPOP10, for the planet Neptune. In addition, Table 4 shows that there are two couples of quite similar ephemerides of Neptune, as they provide the same values of residuals, within only 1 mas, for the period of our observations. These two couples are DE405 and DE406 on one hand, and DE421 and EPM2011m on the other hand, which can be considered as equivalent, respectively. Meantime, we have found that the comparison of our new observations to all the 10 different ephemerides of Triton analysed in this paper present negative mean residuals in declination. Moreover, we can observe that the absolute value of these negative residuals are getting smaller with the development of the newest ephemerides. This shows that the ephemerides could be the reason of such a systematic negative drift of the residuals. However, it seems very difficult to conclude here because there are also other possible factors which could lead to such a result as the reference catalogues which may present some zonal errors, the reduction methods of processing CCD images which can be somewhat different, etc. Due to the relative limitation of the observation amount, a reliable conclusion about this phenomenon cannot be drawn here. So, more observations of Triton with longer time-span,

higher precision and possibly derived from different methods and reference catalogues are needed for the future.

In order to complete the comparison of the different planetary ephemerides, we have compared each of them to DE431 which can be considered as a quite reliable reference because we have shown just above that it is the most accurate among all of those analysed here. So, in Table 5 we present the differences between the theoretical positions of Triton obtained from DE431 and from each of the other planetary ephemerides. For this comparison, neither the two oldest ephemerides DE200 and VSOP87 presenting too high drifts, nor the ephemeris DE406 equivalent to DE405, have been considered. For Triton, we have used the orbit of Jacobson (2009). The differences given in Table 5 have been computed for the three successive oppositions corresponding to the periods of our observations made from 2007 to 2009 and for all the three periods together.

Table 5 shows that INPOP06 is the ephemeris which presents the best agreement with DE431, with no significant difference in declination and less than 10 mas in right ascension. Then, DE421, equivalent to EPM2011m, also presents a rather good agreement with DE431, within less than 20 mas in both coordinates. The other ephemerides DE405, INPOP08 and INPOP10 provide slightly higher differences of about 50 mas. Consequently, this analysis of Table 5 confirms the previous results obtained from Table 4 for the planetary ephemerides. INPOP06 appears to be the most accurate planetary ephemeris, just after DE431 which is the very best one, followed by DE421 and EPM2011m which remain rather accurate ephemerides. Meantime, we have visualized in Fig. 2 the differences versus time of the theoretical positions of Triton derived from each planetary ephemeris with respect to those derived from

Table 5. Differences μ (arcsec) obtained from the comparison between the theoretical positions of Triton derived from the planetary ephemeris DE431 and from six other planetary ephemerides. The orbit model of Triton by Jacobson (2009) is employed. Differences are expressed in arcseconds and computed for each opposition of Neptune from 2007 to 2009 and for all the three periods together.

No.	Planetary ephemerides	2007.08–2007.09		2008.08–2008.09		2009.08–2009.09		2007–2009	
		μ_α (arcsec)	μ_δ (arcsec)						
01	DE421	−0.003	−0.019	−0.001	−0.019	0.001	−0.018	−0.001	−0.018
02	DE405	0.023	−0.047	0.032	−0.046	0.041	−0.044	0.032	−0.045
03	INPOP10	0.020	−0.078	0.022	−0.081	0.025	−0.083	0.022	−0.081
04	INPOP08	0.043	−0.026	0.054	−0.021	0.066	−0.015	0.054	−0.020
05	INPOP06	0.007	−0.000	0.011	−0.004	0.016	0.009	0.011	−0.002
06	EMP2011m	−0.002	−0.018	−0.001	−0.017	0.001	−0.016	0.000	−0.017

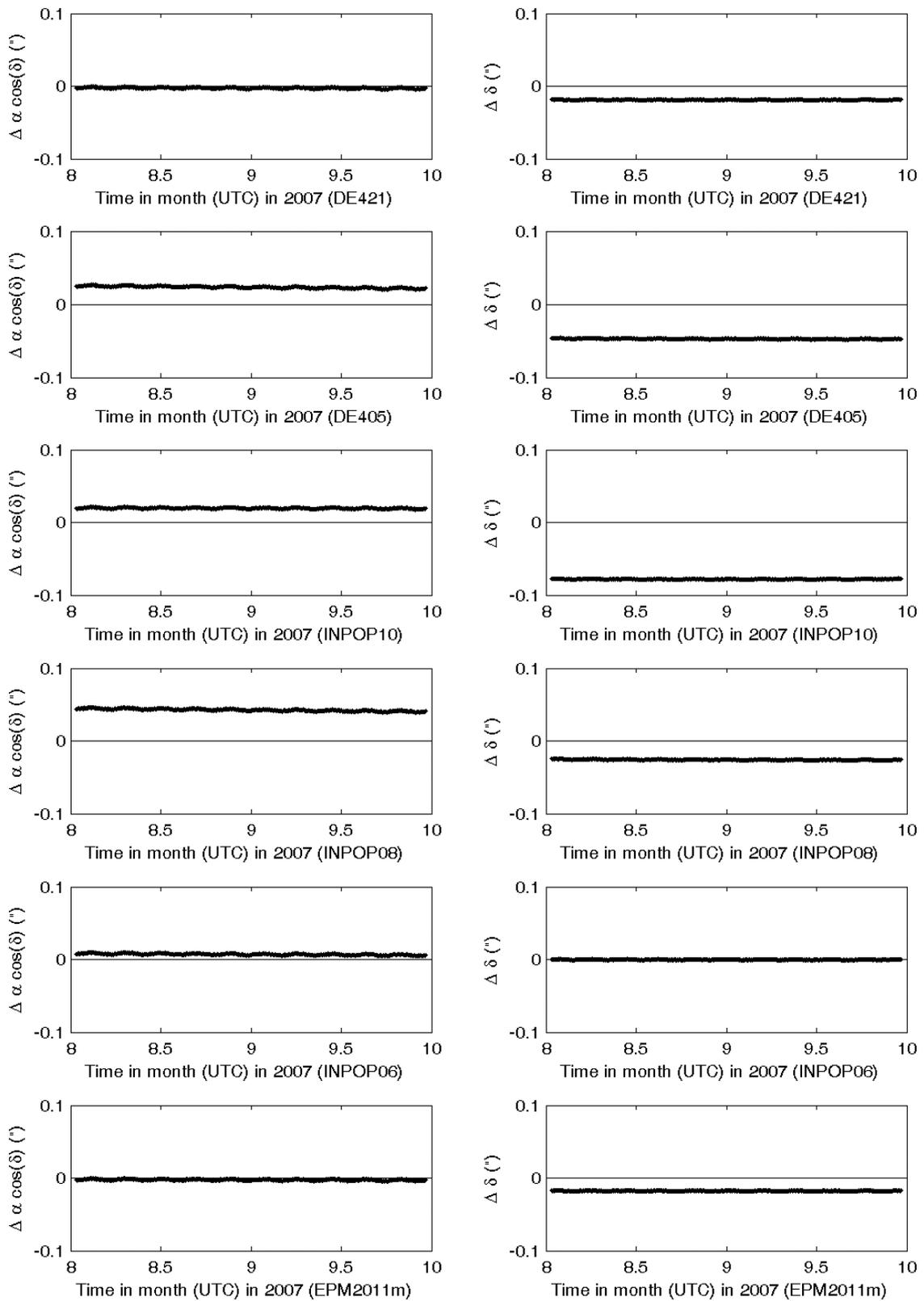


Figure 2. Differences between the positions of Triton successively obtained from different planetary ephemerides of Neptune DE431, DE421, DE405, INPOP10, INPOP08, INPOP06, EPM2011m and from DE431 versus time in 2007 August and September. For Triton, we have used the orbit of Jacobson (2009).

DE431. The plotted differences have been obtained for the period of our observations sets made in 2007 August and September. Fig. 2 confirms the analysis of Table 5 concerning the reliability of each planetary ephemeris. Also, Fig. 2 shows that no significant periodic difference exists between each of the planetary ephemerides, so that they only differ from each other with a variable drift in right ascension and in declination.

5 CONCLUSION

As a continuation of our program of astrometric observations of natural satellites initiated in 1985 including the campaign dedicated to Triton in the period 1996–2006 and reported by Qiao et al. (2007), we have undertaken a second campaign of CCD astrometric observations of Triton, in the period 2007–2009, which we report in this paper. So, we present here 1095 new observed positions of Triton which are being available on the NSDC data base of the IMCCE (Arlot & Emelyanov 2009). The observed data were obtained on three different telescopes. The first one is the 1.56 m reflector at Sheshan station near Shanghai and the two other ones are the telescopes with respective diameters of 2.16 m and 1.00 m located at Xinglong station, near Beijing. During the period of our observations from 2007 to 2009, we undertook eight successive missions over a total of 46 observational nights.

Then, we analysed our observations by comparing them to the best ephemerides of Triton derived from Jacobson (2009), associated with the DE431 planetary ephemeris. This analysis has shown that our observations present a high level of accuracy hardly higher than 50 mas, as it is the average value of the standard deviations of residuals. However, mean residuals are lower, with less than 30 mas in both coordinates, showing the very high accuracy of our observations and of the ephemeris derived from Jacobson (2009) for Triton, associated with DE431 for Neptune.

Also, in order to evaluate and compare the different ephemerides available now, we have compared our observations by using a total of 10 different planetary ephemerides for Neptune and the 2 most recent ephemerides of Triton developed by Jacobson (2009) and by Zhang et al. (2014). For Triton, we have shown that the two orbits (Jacobson 2009 and Zhang et al. 2014) can be considered as equivalent for the recent period of our observations as they provide the same values of mean residuals, within 1 mas, corresponding to only 20 km in the position of Triton.

For the planet Neptune, we have shown that the ephemeris DE431 appears to be the most homogeneous and accurate as it is the only one presenting mean residuals lower than 30 mas in both coordinates, just followed by INPOP06, nearly as accurate than DE431 in both coordinates, within less than 10 mas. Also DE421, that we have shown to be equivalent to EPM2011m, is in very good agreement with DE431, within less than 20 mas. The other planetary ephemerides as DE405, that we have shown to be equivalent to DE406, INPOP08 and INPOP10 present slightly higher residuals but remain in rather good agreement with DE431, within about 50 mas. Finally, DE200 and VSOP82, the oldest ephemerides, present the highest residuals, up to 900 mas, showing a significant drift of their positions for the recent period of our observations.

As we know, for further study on more accurate orbital evolution of Triton, a large number of new precise observations distributed over many nights will be important. Together with those that we published in the previous paper (Qiao et al. 2007), we have obtained a total of 2041 positions of Triton distributed among 66 nights over the period of 1996–2009 with an accuracy of about 50 mas. Therefore, it can undoubtedly be expected that these observations

will be very valuable and significant for any future improvement in the knowledge of Triton, especially for our own research on this satellite, which concerns determining new orbital parameters.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 2. An extract of the list of the observed topocentric equatorial coordinates of Triton, given in the mean equator and equinox of J2000.0 (<http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stu566/-/DC1>).

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