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CCD Astrometric Observations of Phoebe in 2005-2008 ^{★★}

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ABSTRACT

Astrometric observations of Phoebe, the ninth faint satellite of Saturn with visual magnitude of 16.5, were performed during the four successive 2005, 2006, 2007 and 2008 oppositions. **A very important amount of 1173 new observed positions of Phoebe, representing more than 50 percent of the observational data available now,** were obtained during 30 nights of observation involving six missions, by using three different telescopes. The comparison of our observed positions with the JPL Phoebe ephemeris shows the high quality of our observations, **as they appear to be consistent with this ephemeris within only about 50 mas.**

Key words: astrometry - planets and satellites: general

1 INTRODUCTION

Several re-determinations of the orbit of Phoebe were recently made (Arlot et al. 2003, Shen et al. 2005 and Emelyanov 2007). Further update and elaboration of its ephemeris need a considerable accumulation of new observations. However, since its discovery by Pickering (1898), at the end of the 19th century, many observations of the satellite have been hampered because of its faint visual magnitude of about 16.5 and to its great distance away from the primary. In the recent years, the astronomical community has made hard efforts to acquire more observations in different ways. Several amounts of accurate CCD observations of this satellite were **previously obtained in successive works by Veiga et al.(2000), Fienga et al.(2002), Qiao et al. (2006), Peng & Zhang (2006) and by Ekaterina et al. (2010). As a continuation of our previous observing campaign (Qiao et al. 2006), we report in this paper a very important amount of new observations, with a total of 1173 observed positions of Phoebe. Our observations were made**

from 2005 to 2008 and during 30 nights involving six missions. We have used three different telescopes: the 1.56m astrometric reflector at the Sheshan station of Shanghai Astronomical Observatory (SHAO) (E121.184°, N31.096°, H97 m), the 1.00m and the 0.80m reflectors at the Xinglong station of the National Astronomical Observatory (NAO) (E117.577°, N40.396°, H940 m) near Beijing. All these telescopes were equipped with cooled CCD cameras with an array of 2048×2048 pixels for the 1.56m telescope, **1340×1300 pixels for the 1.00m telescope and 1024×1024 pixels for the 0.80m telescope.** Observation and measurement methods are described in Sect. 2. **In Sect. 3, we present an analysis of our observations that we compare to the theory. Finally, in Sect. 4, we report the conclusion of our work.**

2 OBSERVATIONS, MEASUREMENT AND ASTROMETRIC REDUCTION

All the observations of Jan. 2006, Feb. 2007 and Mar. 2008 were made with the 1.56m astrometric reflector equipped with a large liquid-nitrogen-cooled CCD at the Sheshan station. In all of these three missions, we used the binning mode. In this mode the charges of 2×2 pixels could be read out in the process, so that we could get a higher signal-to-noise ratio during the observation. Consequently, the pixel

* 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-strasbg.fr or via <http://cdsweb.u-strasbg.fr/Abstract.html>.

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Table 1. Specifications of the three telescopes and CCD chips used for the observations of Phoebe, the 9th Saturnian faint satellite.

	Telescope A	Telescope B	Telescope C
Diameter of primary mirror	156cm	100cm	80cm
Focal length	15600mm	7800mm	8000mm
Size of CCD array (pixel)	2048x2048	1340x1300	1024x1024
Size of pixel	24 μ m	20 μ m	13 μ m
Angular extent per pixel	0.32''	0.53''	0.30''
Field of view	11.2'x10.8'	11.7'x11.4'	5.2'x5.2'

number became 1024x1024 pixels and the size of each pixel was then 48 μ m. **The exposure time varies from 30s to 180s, depending on the meteorological conditions.** In the observing missions of Mar. 2007 and Feb. 2008, we used the 1.00m telescope and the exposure time varies from 20s to 120s. In the mission made in Jan. and Feb. 2005, the 0.80m telescope was used and the exposure time varies from 40s to 180s. No filter was used in these six campaigns. For more instrumental details about the CCD detectors and the reflectors, see Table 1.

For the measurement process of the CCD frames, we used the powerful *Astrometrica* software. So, all the successive steps as image calibration including dark frame and flat field corrections, rejection of the single bright pixels, extraction of the background level, determination of the center of images and identification of the catalogued stars and of Phoebe have been performed with this software. More information about the measurement process can be found in Qiao et al. (2008).

Because of the advantage of the CCD chips mounted on the three used telescopes, due to their wide fields slightly greater than 10.0'x10.0', a high number of catalogued stars, generally from 15 to 20, were available in the frames. Consequently, a second order polynomial with 12 constants could be used in the astrometric calibration process. However, for some frames presenting a lower number of catalogued stars, a linear polynomial with 6 constants has been preferred.

Also, for the astrometric reduction process, the UCAC2 CCD Astrograph catalog has been chosen as reference star catalog. The UCAC2 (Zacharias et al., 2004) is one of the most accurate high density astrometric catalog available now. We preferred it to the UCAC3 although providing a higher density (Zacharias et al. 2010), because we have shown that UCAC3 can present some significant zonal errors in the zone of our observations of Phoebe in 2005-2008. Such errors in star catalogs were previously pointed out and estimated by several authors as Fienga & Andrei (2002) and more recently Roeser et al. (2010) and Krone-Martins et al. (2010). In this latest work, Krone-Martins et al. have shown that UCAC3 could present higher systematic zonal errors than UCAC2 in a large zone that overlaps the zone where Phoebe was located in 2005-2008. So, we have checked if any systematic error could affect this particular zone of our observations of Phoebe (7h< α <10h and 11°< δ <21°). In this purpose, we have compared the observed positions of the com-

Table 2. An extract of the list of the observed topocentric equatorial coordinates of Phoebe, given in the mean equator and equinox of J2000.0

Year	Month	Day(UTC)	α (hms)	δ (dms)
2005	01	29.542014	7 35 44.075	+21 38 43.30
2005	01	29.544792	7 35 44.027	+21 38 43.27
2005	01	29.547569	7 35 43.957	+21 38 43.41
2005	01	29.550336	7 35 43.925	+21 38 43.68
2005	01	29.553819	7 35 43.854	+21 38 43.93

mon Tycho2 stars present in the fields with their catalogued positions. This has shown that some systematic zonal errors, up to 70 mas, could exist in this zone when using UCAC3. Similarly, when using UCAC2, we have determined that zonal errors generally remain below 10 mas, which is rather insignificant. Consequently, as the density of the UCAC2 was quite sufficient for the astrometric reduction, we preferred it to the UCAC3. In addition, our determination of zonal errors in the zone of Phoebe confirms the previous similar results obtained by Krone-Martins et al. (2010).

The UCAC2 covers a wide range of magnitude from about 9 to 16 and provides the positions and proper motions of more than 48 million stars, given at the epoch J2000.0., on the International Celestial Reference System (ICRS). Zacharias et al. (2004) claim that the positional accuracy of stars in UCAC2 is between 15 and 70 mas, depending on the magnitude, and that systematic zonal errors are of 10 mas or below, what we have confirmed just above for the particular zone of Phoebe in 2005-2008.

Table 2 presents an extract from the list of the observed positions of Phoebe. The first three columns of Table 2 are the year, month and decimal day in UTC of the middle time of each observation. In the next two columns, we list Phoebe right ascension, expressed in hour, minute and seconds of time, and declination, expressed in degree, minute and arcseconds. These equatorial coordinates are topocentric and given in the mean equator and equinox of J2000.0. The complete data can be obtained on the web site of the CDS at the following address: <http://cdsweb.u-strasbg.fr/Abstract.html>, or via Anonymous FTP to cdsarc.u-strasbg.fr.

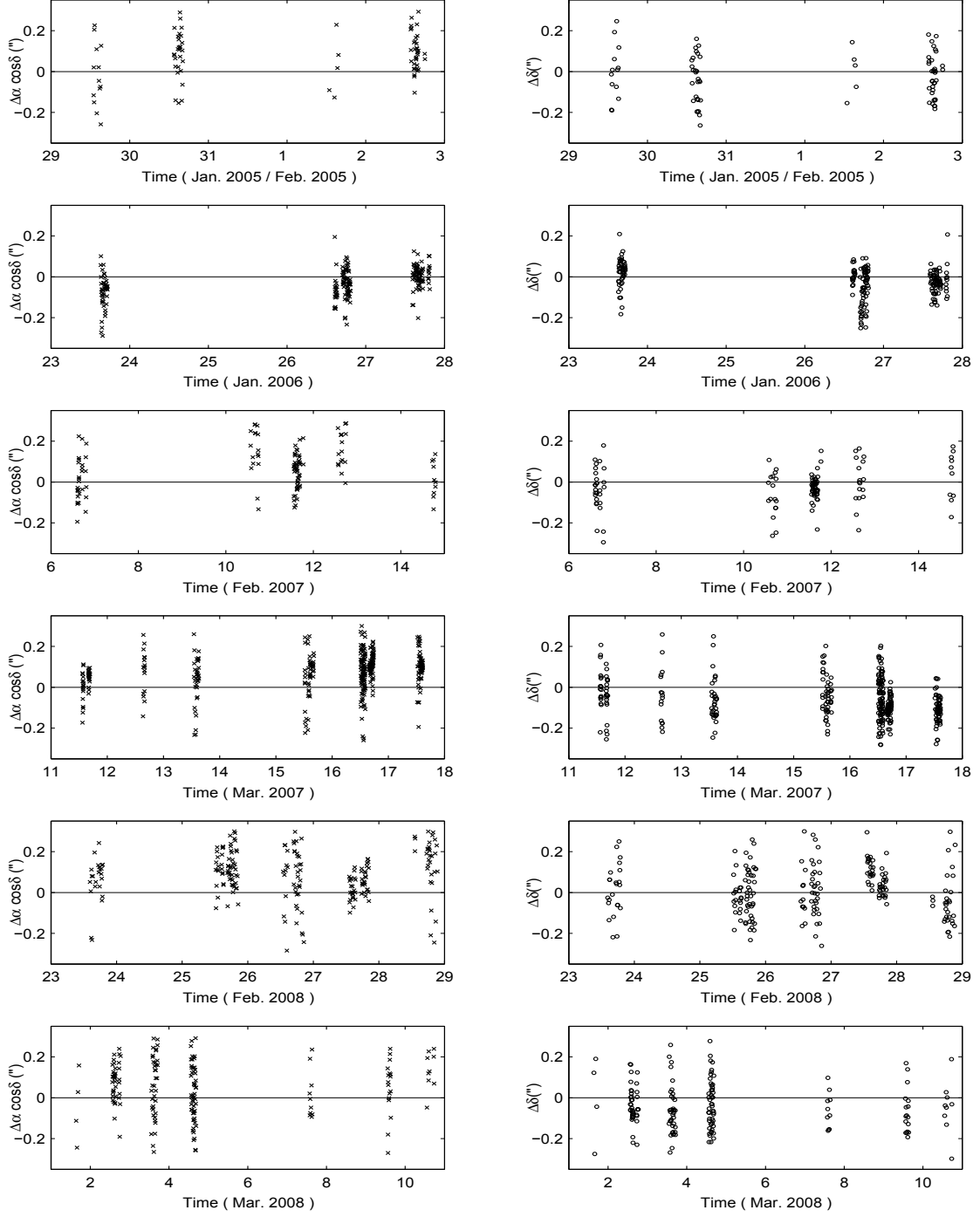


Figure 1. (O-C) of Phoebe in 2005-2008 relative to the six sets of observations, derived from the comparison of all our observations to the JPL SAT317 ephemeris. From above to below, we successively used the 0.80m, 1.56m, 1.56m, 1.00m, 1.00m and the 1.56m telescopes.

Table 3. Values of mean residuals (O-C) μ and standard deviations to the mean σ computed for each of the 30 nights of observations of our 6 missions and for all the observations. N is the number of the observed positions of Phoebe for each night or for all observations.

Date	N	$\mu(^{\circ})$ $\Delta\alpha\cos\delta$	$\mu(^{\circ})$ $\Delta\delta$	$\sigma(^{\circ})$ $\Delta\alpha\cos\delta$	$\sigma(^{\circ})$ $\Delta\delta$
2005 1 29	13	-0.017	-0.001	0.152	0.134
2005 1 30	28	0.085	-0.042	0.114	0.117
2005 2 01	5	0.022	0.001	0.142	0.117
2005 2 02	35	0.097	-0.022	0.088	0.103
2006 1 23	50	-0.073	0.024	0.080	0.068
2006 1 26	88	-0.039	-0.041	0.070	0.087
2006 1 27	79	0.005	-0.028	0.053	0.053
2007 2 06	28	0.011	-0.036	0.107	0.108
2007 2 10	17	0.150	-0.061	0.121	0.107
2007 2 11	49	0.049	-0.025	0.082	0.059
2007 2 12	17	0.162	0.002	0.090	0.111
2007 2 14	10	0.015	0.027	0.089	0.117
2007 3 11	39	0.025	-0.023	0.065	0.103
2007 3 12	16	0.077	-0.038	0.110	0.136
2007 3 13	34	0.032	-0.064	0.117	0.106
2007 3 15	48	0.050	-0.037	0.118	0.097
2007 3 16	179	0.087	-0.072	0.088	0.090
2007 3 17	61	0.097	-0.109	0.081	0.066
2008 2 23	23	0.060	0.013	0.111	0.125
2008 2 25	63	0.119	-0.009	0.087	0.113
2008 2 26	43	0.063	0.008	0.150	0.129
2008 2 27	49	0.042	0.072	0.063	0.071
2008 2 28	31	0.142	-0.044	0.141	0.126
2008 3 01	4	-0.043	-0.002	0.174	0.207
2008 3 02	39	0.077	-0.034	0.091	0.091
2008 3 03	37	0.056	-0.064	0.153	0.121
2008 3 04	52	0.017	-0.030	0.139	0.118
2008 3 07	10	0.012	-0.060	0.118	0.088
2008 3 09	17	0.051	-0.066	0.135	0.110
2008 3 10	9	0.135	-0.047	0.092	0.130
All	1173	0.052	-0.034	0.113	0.104

3 COMPARISON WITH THEORETICAL POSITIONS

In order to check and analyse our observations, we have compared them to the theoretical positions of Phoebe available on the JPL's Horizons system.

These positions are derived from the SAT317 satellite ephemeris (Jacobson et al. 2006) for Phoebe, associated with the DE405 (Standish 1998; 2004) planetary ephemeris for Saturn. The SAT317 ephemeris of Phoebe was generated by fitting the integrated orbit of this satellite to earth-based observations and to data obtained with spacecrafts including Pioneer 11, Voyager 1&2, Hubble Space Telescope and more recently, Cassini.

All our observations have then been compared to these computed positions. A rejection level of 0.3 arcsec has been used and the so-obtained residuals (O-C), plotted versus time, are presented in Fig. 1 for each of

the six missions from 2005 to 2008. Fig.1 shows that the absolute value of residuals remains lower than 0.2 arcsec. In addition, the values of mean residuals and standard deviations derived from this comparison to the JPL ephemeris are presented in Table 3 for each of the 30 successive nights of observation and for the whole set of observations.

The accuracy of our observations can be evaluated to 0.1 arcsec, as it is approximately the value of standard deviations, given in Table 3, for all the observations. Moreover, Table 3 shows that the values of mean residuals for all the observations remain lower than 50 mas. So, our observations appear quite consistent with the JPL ephemeris, within only 50 mas.

Due to their high accuracy evaluated just above, our observations should be very valuable for future improvements of Phoebe orbit. Also, the 1173 new positions of Phoebe presented here should be particularly valuable because they represent more than 50 percent of all the positional data of this satellite available now, as 2044 positions have already been collected by the Centre de Données des Satellites Naturels (CDSN) data base of the IMCCE.

4 CONCLUSION

As a continuation of our program of astrometric observations of natural satellites initiated in 1985, we have issued our second campaign of CCD astrometric observations of Phoebe, the first one being previously reported by Qiao et al. (2006). In this paper, we have presented a very important amount of observations of Phoebe, with 1173 new observed positions of this satellite which represents more than 50 percent of the data available now on the CDSN data base of the IMCCE. They were obtained on the 1.56m reflector at the Sheshan station of Shanghai and on the 1.00m and the 0.80m telescopes at the Xinglong station, near Beijing. These observations were spreading over the period from 2005 to 2008. During this period, we made 6 successive missions with a total of 30 nights of observations. We have analyzed our observations by comparing them to the theoretical positions of Phoebe available on the JPL's Horizons system. This analysis has shown that our observations present a quite satisfactory level of accuracy, with about 100 mas. Also, we have shown that our observations appear to be in quite good agreement with the JPL ephemeris, within a lower value of only 50 mas.

Therefore, it can undoubtedly be expected that these observations will be very valuable and significant for any future improvement of the knowledge of Phoebe, especially for our own research on this satellite, in which we are intending to determine new orbital parameters.

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