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Updated Phoebe's orbit

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ABSTRACT

In recent years, many new CCD observations of Phoebe, the ninth Saturnian satellite, were published. In this paper, we have used all the observations of Phoebe available until 2009 to update Phoebe's orbit. These observations represent a total number of 2994 positions, spread over a time-interval of 105 years, from 1904 to 2009. The accuracy of the updated orbit of Phoebe presented here has been improved to about 0.1 arcsec as it has been fitted to a large number of new high-accuracy observations. However, the accuracy of the orbit remains limited by the accuracy of the observations. Moreover, we have shown that the new orbit is in quite good agreement with the very reliable JPL ephemeris, within less than 20 mas.

Key words: planets and satellites: individual: Phoebe – planets and satellites: individual: Saturn.

1 INTRODUCTION

A reliable model of satellite motion must be constructed with high-accuracy observations and with data spreading over a period as long as possible. On the basis of the new observations published in the last 10 years, the ephemeris of Phoebe, the ninth satellite of Saturn, has been constantly updated through a series of works, for example, by Jacobson (1998), Arlot et al. (2003), Shen et al. (2005) and Emelyanov (2007). The quick increase in the number of observations used in recent orbit determinations has been illustrated in the two latter works which used 686 and 1606 observations, respectively.

Since Emelyanov's work in 2007, we have collected 1388 new CCD observations that are listed in Table 1. Among all these new observations, those made by Qiao et al. (2011) represent the most important observations, 1173 in number, spread over a 4 year period from 2005 to 2008. Such a large number of new CCD observations provided a good opportunity for a further update of Phoebe's orbit. Thus, in this paper, we have carried out a new determination of the orbit of Phoebe by using all the observational data available until 2009, spread over a 105 year period, from 1904 to 2009. These data represent a very large number of 2994 observations, including the 1606 observations previously published by Emelyanov (2007) and

the above-mentioned 1388 new observations published since 2007. The use of such a large number of observations should ensure an efficient update of Phoebe's orbit.

2 OBSERVATIONS AND REFERENCE FRAME

2.1 New sources of observations

First of all, we have used 1606 observations made from 1904 to 2007 and already published by Emelyanov (2007). These observations are available on the website of the IMCCE Natural Satellite Data Center: <http://www.imcce.fr/nsdc>. A detailed list of these observations made in 39 different observatories is given in table 1 of Emelyanov (2007).

Moreover, we have collected 1388 new observations of Phoebe made after 2007 in nine different observatories (see Table 1). Among these new observations, we especially mention the 1173 CCD observations made over the period 2005–08 by Qiao et al. (2011) at the Sheshan Station, as these form the largest observational set, and we will also show later in this work that it is also the most accurate set we have used here. All the new sources of observations that we have used for determining the new orbit of Phoebe are listed in Table 1. All observatories listed in Table 1, except two of them, Andrushivka and Purple Mountain, have contributed to previous Phoebe's observations and were already mentioned by Emelyanov (2007). As the observations used by Emelyanov were made in 39

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Table 1. List of the 1388 new observations made since 2007 and first used here for the redetermination of Phoebe's orbit. N_u is the number of the satellite positions used.

Observatory code	Observatory name	Period of observation	N_u
337, 327	Sheshan, Xinglong	2005–08	1173
415	Kambah	2007	149
673	Table Mountain	2009	8
688	Lowell	2009	8
689	Flagstaff	2008	19
691	Kitt Peak	2007	9
704	New Mexico	2009	10
A50	Andrushivka	2008	7
D29	Purple Mountain	2009	5

different observatories, the observations used here are from a total of 41 different observatories. Thus, our updated Phoebe's orbit is based on very important 2994 observations of Phoebe, spread over 105 years from 1904 to 2009 and made in 41 different observatories. This number (2994) is about twice the number of the observations used in the last Phoebe's orbit determination by Emelyanov (2007) and five times higher than the number of the observations used in the next-to-last determination by Shen et al. (2005).

2.2 Reference frame

All the observations made were with reference to different reference frames. Consequently, some corrections have been made to ensure good consistency between them. First of all, the photographic observations presented in the catalogue of Bec-Borsenberger & Rocher (1982) were reduced to the mean equator and equinox B1950 in the FK4 system. Thus, we have rotated the vectors of satellite positions from FK4/B1950 to FK5/J2000 by using the precession matrix and the procedure proposed by Aoki et al. (1983). Then, CCD observations by Peng & Zhang (2006) were made at the epoch of date and in apparent geocentric coordinates. Thus, we have rotated the vectors of satellite positions to the epoch of J2000. Finally, all other new CCD observations were derived from catalogues given in the ICRF with reference to the FK5/J2000 system. Consequently, no correction has been made for these observations.

3 CALCULATION PROCESS AND ORBIT DETERMINATION

3.1 Perturbations

For the perturbations, as in our previous orbit determination of Phoebe (Shen et al. 2005), the Sun is still regarded as the overwhelming source. We have also included in the equations of motion the perturbations by Jupiter and Uranus. Their positions are computed from the planetary ephemeris DE421. The additional perturbation due to the oblateness (J_2) of Saturn is also considered, although a test calculation has shown that its inclusion has no significant effect. For the inner planets, the effects have been checked to be so small that they can be neglected.

As Titan is the most massive body orbiting in the Saturnian system, its perturbations on Phoebe were taken into account in most of the previous investigations by Jacobson (1998), Arlot et al. (2003) and Shen et al. (2005).

Although Jacobson (1998) has shown that the perturbations by Titan are so small that they can be neglected, we have considered them in our model, as those due to all the eight major Saturnian

Table 2. Dynamical constants used in this study and derived from Jacobson et al. (2006) for the Saturnian system and from Jacobson (private communication) for the planets.

Constant	Value	Units
Saturn mass	2.85886D−4	(Per solar mass)
Jupiter mass	3.339 76	(Per saturn mass)
Uranus mass	0.152 727	(Per Saturn mass)
Mimas mass	6.597D−8	(Per Saturn mass)
Encelade mass	1.9007D−7	(Per Saturn mass)
Tethys mass	1.286D−6	(Per Saturn mass)
Dione mass	1.9275D−6	(Per Saturn mass)
Rhea mass	4.05844D−6	(Per Saturn mass)
Titan mass	2.3669D−4	(Per Saturn mass)
Iapetus mass	3.17711D−6	(Per Saturn mass)
Phoebe mass	0.0005D−4	(Per Saturn mass)
Saturn's J_2	0.0162 99	

satellites. For that purpose, we have augmented the mass of Saturn by the mass of the eight major satellites, including Titan. The values of J_2 have also been corrected to take into account the perturbations by the major satellites. The adopted values for these parameters are given in Table 2. They are derived from Jacobson et al. (2006) for the Saturnian system and from Jacobson (private communication) for the planets.

3.2 Calculation of the updated Phoebe's orbit

We apply the same process for the numerical integration as we followed earlier (Shen et al. 2005). The calculated Phoebe's orbit was generated by a numerical integration of its equations of motion expressed in Saturncentric rectangular coordinates with reference to the Earth mean equator and equinox of the J2000 system (ICRF). We start from the same initial conditions and at the same epoch (JD 244 0600.5). These sets of initial coordinates and velocities are given in Table 3.

The integration was carried out using a 12th-order Runge–Kutta–Nystrom formula with the variable-step-size method. An absolute truncation error limit of 10^{-10} km s $^{-1}$ imposed on velocity controlled the integration step.

During preliminary analysis, 44 observed positions of Phoebe causing residuals in right ascension and declination of more than 2.5 arcsec were rejected.

In order to characterize the different quality of each set of observations, we have attributed to each of these sets a weight numerically equal to the reciprocal of the standard error of the corresponding set.

Also, we have confirmed that the corrections of -0.75 arcsec applied to the right ascension of all the observations made prior to 1940 by different authors, such as Jacobson (2000) for the Jovian satellites and Emelyanov (2007) for the Saturnian satellites, led to a significant improvement in the residuals (Figs 1a and b). Hence,

Table 3. Saturncentric starting state vector at JD 244 0600.5 with reference to the Earth mean equator and equinox of J2000.

Component	Position (au)	Velocity (au d $^{-1}$)
x	−0.8222905954738 D − 01	0.2850503488894D−03
y	0.3486032881561 D − 01	0.7988457450202D−03
z	0.2605021532973 D − 01	0.3433375379172D−03

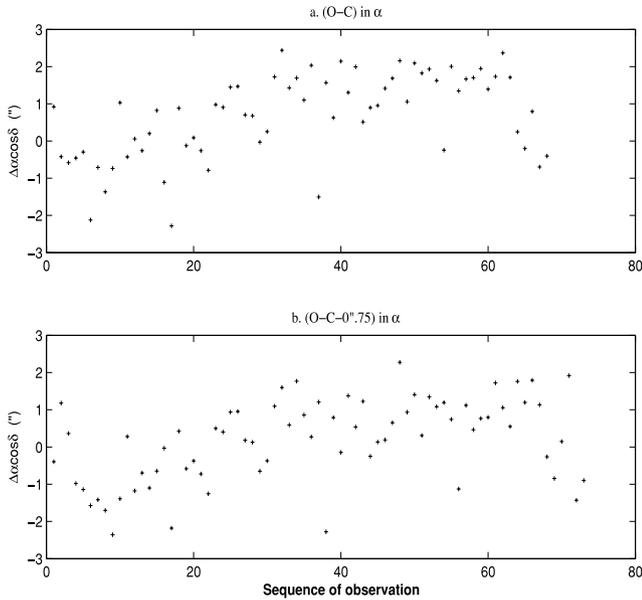


Figure 1. Plots of O–C residuals in right ascension of the photographic observations from an integration fit to all observations. (a): no additional correction; (b): an additional correction of -0.75 arcsec is applied to the right ascension of the photographic observations prior to 1940.

Table 4. The resulting initial conditions for Phoebe after least-squares orbit adjustment at JD 244 0600.5.

Component	Position (au)	Velocity (au d^{-1})
x	$-.8222971225450D - 01$	$.2851019713340D-03$
y	$.3487253432435D - 01$	$.7987119269534D-03$
z	$.2605950144252D - 01$	$.3433839208685D-03$

Table 5. Planetocentric mean orbital elements at JD 244 0600.5 with reference to Phoebe's Laplacian plane.

Element	Value	Element	Value
a	0.086 072 au	λ	$39^{\circ}265$
e	0.185 21	ω	$228^{\circ}251$
i	$174^{\circ}671$	Ω	$242^{\circ}328$
n	$0^{\circ}659932 \text{ d}^{-1}$		
α_L	$271^{\circ}631$		
δ_L	$68^{\circ}031$		

Notes. n : mean motion; α_L : Laplacian plane pole right ascension; δ_L : Laplacian plane pole declination.

we have also applied such a correction which is due to the offset between Newcomb's equinox and that of FK4 before 1940, as shown by Jacobson (2000).

After integration runs, the resulting epoch state vector was obtained and the results are listed in Table 4.

We have computed the mean elements corresponding to the epoch state vector at JD 244 0600.5. The values thus obtained are presented in Table 5. The mean elements are with reference to the Laplacian plane of Phoebe. The adopted values for orientation angles of the Laplacian plane pole with respect to the Earth mean equator and equinox of J2000 (α_L and δ_L) are derived from Jacobson (2006).

4 ANALYSIS AND ACCURACY

All the available observations of Phoebe are absolute positions derived from a large variety of star catalogues. Consequently, these observed positions can be affected by possible significant systematic errors due to the errors of catalogues. For photographic observations made before 1970, the rms of O–C residuals in right ascension and declination, and their standard deviations about the mean derived from our new orbit are given in Table 6. For CCD observations made after 1970, the same statistics are presented in Table 7. The corresponding plots versus time of the O–C residuals for the photographic observations prior to 1970 are shown in Fig. 2. Similarly, the O–C residuals versus time for the CCD observations made after 1970 are shown in Fig. 3.

Table 7 shows that the two recent observational sets made by Qiao et al. (2006) and Qiao et al. (2011) at the Sheshan Station are the most accurate. These two sets, respectively, contain 101 observations made in 2003 and 1173 observations made in the period 2005–08. The quite good accuracy of these two recent sets may be due to not only improvement in the observing technique, but also use of the high-quality UCAC2 star catalogue. Concerning that point, we can refer to Arlot et al. (2003) who emphasized that any improvement in the star catalogue used for the reduction of

Table 6. The mean residuals μ (arcsec) and standard deviations σ (arcsec) of the O–C residuals about the mean for the photographic observations. N_u is the number of the observations used in the reduction. The first column gives the code for each observatory.

Code	Observatory	Year	N_u	μ_α	μ_δ	σ_α	σ_δ
0	Greenwich	1907	48	0.37	0.19	0.93	0.84
74	Boyden	1957	8	-0.04	1.47	0.71	0.66
662	Lick	1904	19	-0.66	-0.44	0.96	0.87
688	Lowell	1981	8	0.44	-1.26	0.76	0.53
695	Kitt Peak	1969	5	-0.02	0.36	0.53	0.29
711	McDonald	1942	16	1.25	-0.13	0.62	0.68
822	Cordoba	1952	7	0.06	0.04	0.92	0.32

Table 7. The mean residuals μ (arcsec) and standard deviations σ (arcsec) of the O–C residuals about the mean for the CCD observations. N_u is the number of the observations used in the reduction. Only the observatories with $N_u > 30$ are included in the table. The first column gives the code for each observatory.

Code	Station	Year	N_u	μ_α	μ_δ	σ_α	σ_δ
286	Yunan	2003–05	210	0.32	0.04	0.24	0.09
337	Sheshan	2003	101	-0.05	-0.03	0.08	0.08
337/327	Sheshan/Xinglong	2005–08	1173	-0.09	0.02	0.15	0.10
415	Kambah	2004–07	401	0.25	0.01	0.35	0.27
511	Haute	1998–99	161	-0.20	0.07	0.18	0.20
673	Table Mountain	2001–05	127	0.16	-0.02	0.29	0.24
689	Flagstaff	1998–2005	254	-0.08	-0.01	0.40	0.39
691	Kitt Peak	2000–07	32	0.01	0.20	0.29	0.23
704	New Mexico	1998–2007	164	-0.04	0.33	0.75	0.87
809	ESO	1981–2000	66	0.23	-0.12	0.67	0.73
874	Itajuba	1995–97	60	-0.25	0.15	0.23	0.31

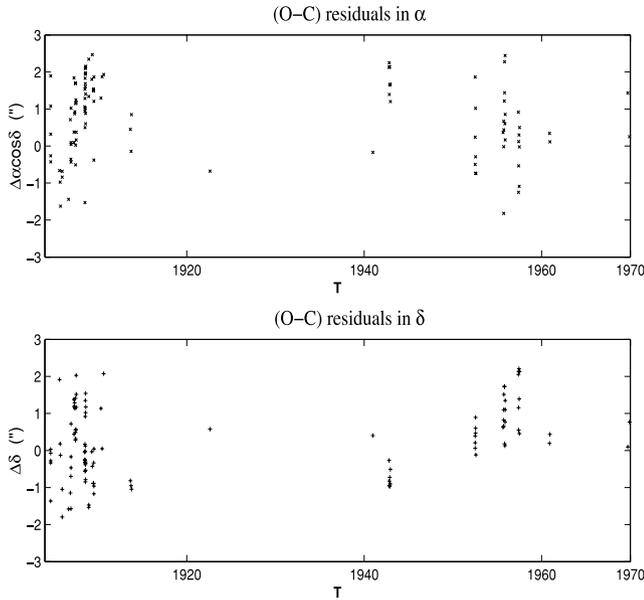


Figure 2. Plots of O–C residuals in right ascension (upper panel) and declination (lower panel) from an integration fit to all the photographic observations over the period 1904–69.

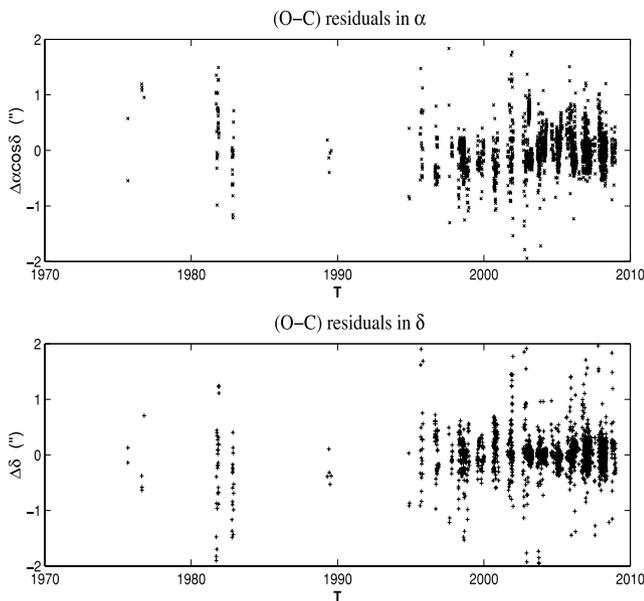


Figure 3. Plots of O–C residuals in right ascension (upper panel) and declination (lower panel) from an integration fit to all CCD observations over the period 1970–2009.

the observations greatly helps to increase the level of accuracy of observations. In this work, both these new very accurate observational sets including a significant number of positions have been incorporated in our orbit determination of Phoebe. These new sets have allowed us to establish an improved ephemeris of this satellite, with an accuracy that we can evaluate to about 0.1 arcsec, corresponding to the average value of standard deviations of these recent high-quality observational sets. However, the accuracy of the new orbit remains limited by the accuracy of the observations.

5 COMPARISON WITH PREVIOUS EPHEMERIDES

For providing a quantitative comparison of the updated Phoebe orbit with the earlier orbits by Shen et al. (2005) and Emelyanov (2007), and with the JPL ephemeris, we have compared a brand new set of 22 CCD observations of Phoebe, made in 2010 January 17 by Qiao et al. (2011), with these four different orbits. We have chosen these new observations because they had not been previously used by any author, including us, to update the orbit of Phoebe. Consequently, their comparison with the new orbit cannot present any favourable bias it could have presented had we chosen any new observations used only by us to update the Phoebe orbit.

Table 8 and Fig. 4 present the results of this comparison. In Table 8, we can observe that all the ephemerides of Phoebe present nearly-equal rms residuals of about 0.1 arcsec. This is not surprising because rms residuals are mainly dependant on the accuracy of the observations. Thus, this brand new set of observations present an accuracy close to 0.10 arcsec. Also, we can observe in Table 8 that our mean residuals in right ascension (59 mas) are the lowest ones, just after the JPL ones (53 mas). In declination, our mean residuals (–62 mas) do not have as low amplitude as Emelyanov’s residuals (23 mas), but they are the closest ones to the JPL residuals (–49 mas). Finally, Table 8 shows that among the four different orbits, ours is the one presenting the best agreement with the JPL ephemeris, which is the best ephemeris of Phoebe available today. This quite good agreement of our orbit with JPL’s does not exceed

Table 8. The residuals resulting from comparing the three ephemerides to the 2010 new observations.

Ephemeris	μ_α	rms	μ_δ	rms
Shen (old)	0.1458	0.1045	–0.1535	0.1075
Shen (new)	0.0593	0.1042	–0.0620	0.1074
Emelyanov	–0.1219	0.1044	0.0231	0.1075
JPL	0.0530	0.1043	–0.0430	0.1074

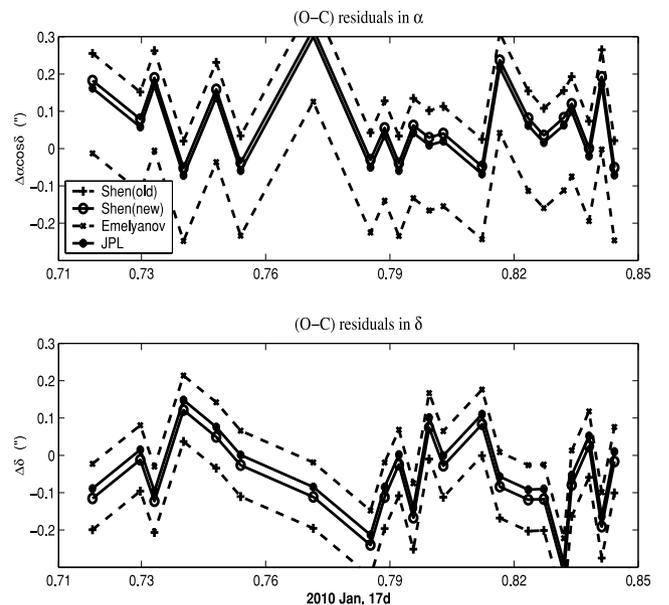


Figure 4. Plots of the O–C residuals of the three different ephemerides to the brand new CCD observations made on 2010 January 17. Symbols: ‘+’: Shen et al.’s, (2005) old ephemeris; ‘o’: Shen’s new ephemeris; ‘x’: Emelyanov’s ephemeris; ‘•’: JPL ephemeris.

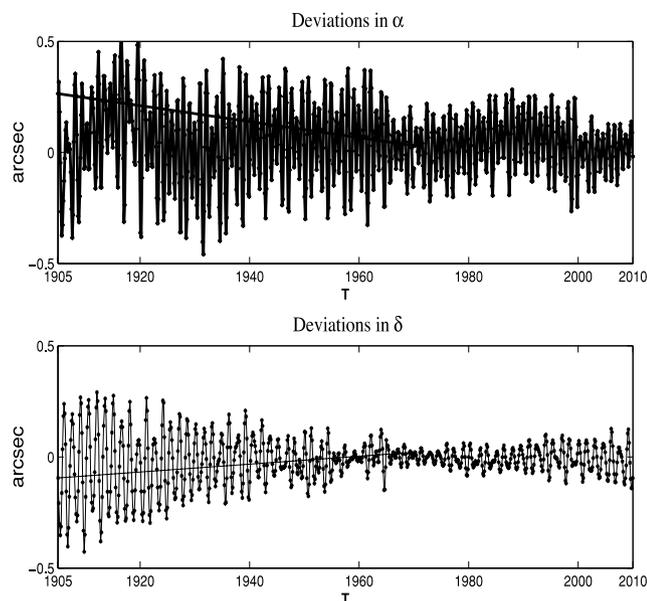


Figure 5. Plots of the deviations between the JPL ephemeris and ours in right ascension (upper panel) and declination (lower panel) in the observing period 1905–2009 of Phoebe.

6 mas in right ascension and 19 mas in declination for this set of 22 brand new observations made by Qiao (personal communication) in 2010 January. As these observations have not been used by any authors, the values obtained from this comparison and given above cannot present any favourable bias for any orbit, including ours. This emphasizes the high reliability of our new orbit, as it is the closest to the JPL ephemeris, within less than 20 mas. This result appears to be quite satisfactory for a small and faint satellite like Phoebe.

Also, we have made a comparison of the new orbit with the JPL ephemeris for the time-interval 1905–2009. Fig. 5 shows the deviations between the two orbits, computed in time-steps of 50 days. In Fig. 5, we can see periodic differences in right ascension and declination, with residuals reduced for the recent period. In recent years, the deviations between our orbits and JPL's have not exceeded 0.1 arcsec, so that they remain within the errors of the observations.

6 CONCLUSIONS

In this paper, we have reported an updated orbit of Phoebe. We have computed this orbit from a numerical integration fit to all the 2994 observed positions of this satellite available until 2009. These are ground-based observations spread over 105 years from 1904 to 2009 and made in 41 different observatories. The updated orbit presented here has been established by using much more observations than all previous orbit determinations of this satellite. For example, we have used about twice the number of the observations used in the last determination by Emelyanov (2007) and nearly five times more observations than used in the next-to-last determination by Shen et al. (2005). This large number of recent, high-quality observations have contributed in obtaining an improved updated orbit of Phoebe, with an accuracy of about 0.1 arcsec. However, the orbit

accuracy remains limited by the accuracy of the available observations. Furthermore, we have compared our new orbit with the earlier two orbits (Shen et al. 2005; Emelyanov 2007) and with the JPL ephemeris. We have also compared with these four different orbits a brand new set of 22 observations made by Qiao (personal communication), never used previously by any authors, including us, for improving Phoebe's orbit. This avoids any possible bias which could have occurred had the comparison involved observations already used to update one of these orbits. This has shown that our new orbit is the best one in right ascension and presents the lowest mean residuals in right ascension. Thus, if it presents mean residuals in declination slightly higher than Emelyanov's (2007), then our new orbit is the one presenting the best agreement with the JPL reliable ephemeris in right ascension, within only 6 mas, as well as in declination, within 19 mas.

This is a quite good result for such a small satellite orbiting rather far from Saturn, and necessarily with reference to absolute positions, when inner satellites with reference to relative intersatellite positions can be expected to be more accurate, as they are less affected by possible systematic errors of star catalogues. However, the improvement in star catalogues, such as UCAC2 used by some recent authors like Qiao et al. (2006, 2011), has limited the effect of these possible systematic errors in the recent past. The use of this latest accurate catalogue has also contributed to present here a more reliable updated orbit of Phoebe.

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