ASTRONOMY & ASTROPHYSICS
SUPPLEMENT SERIES

FEBRUARY II **2000**, PAGE 81

Astron. Astrophys. Suppl. Ser. **142**, 81–84 (2000)

CCD observations of Phoebe*,**

C.H. Veiga, R. Vieira Martins, and A.H. Andrei

Observatório Nacional, Rua Gal. José Cristino 77, 20921-400 Rio de Janeiro, Brazil
e-mail: cave@on.br or rvm@on.br

Received July 13; accepted November 19, 1999

Abstract. Astromeric CCD positions of the Saturnian satellite Phoebe obtained from 60 frames taken in 10 nights are presented. The observations were distributed between 5 missions in the years 1995 to 1997. For the astrometric calibration the USNO-A2.0 Catalogue is used. All positions are compared with those calculated by Jacobson (1998a) and Bec-Borsenberger & Rocher (1982). The residuals have mean and standard deviation smaller than 0.″5, in the x and y directions. The distribution of residuals is suggestive of the need of an improvement for the orbit calculations.

Key words: astrometry — planets and satellites — Saturn

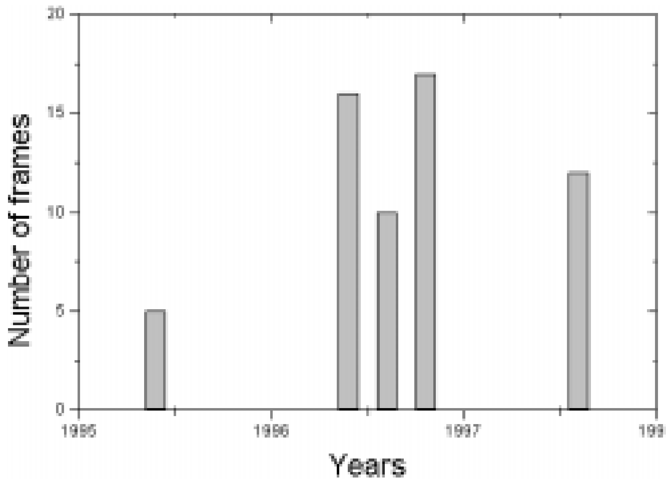

Fig. 1. Distribution of the observations. Every bar corresponds to an observational mission

1. Introduction

Phoebe is the most distant known satellite of Saturn. Its distance from the planet is larger than 12 million kilometers which gives an elongation larger than 34′. Its eccentricity is about 0.16 and its visual magnitude is larger than 16.

After its discovery in 1898 by E.C. Pickering (1899), there were more than four hundred astrometric observations of this satellite, made in 42 observational sets (Jacobson 1998b). These sets are not well distributed in time. In particular, from 1982 on there are available 66 ground observations, made at USNO and at McDonald. From these, only 21 had been made with CCD. When compared with Jacobson's orbit, a quarter of all observations have residuals with σ smaller than 0.″5, and almost all recent observations are included in this group.

In this paper we present a set of 60 CCD new positions of Phoebe, from observations carried out in 1995, 1996 and 1997. The observations and measurements are presented in Sect. 2. In Sect. 3 we present an astrometric calibration procedure using the USNO-A2.0 Catalog and in Sect. 4 the observations and the theoretical positions given by Jacobson (1998a) and Bec-Borsenberger & Rocher (1982) are compared. The conclusion is presented in the last section.

2. The observations and measurements

All observations were made at the Cassegrain-focus of the 1.6 m Ritchey-Chretien reflector of the Laboratório Nacional de Astrofísica in Brazil (geographical longitude: $3^{\rm h}02^{\rm m}19^{\rm s}$, latitude:$-22^{0}32'04''$ and altitude: 1872 m). The focal length of the Cassegrain combination is 15.8 m, which results in a plate scale of 13.″0/mm at the focal plane.

Along the various missions, three CCD detectors were used: CCDs EEV P88231, EEV-05.20.0.202 and SITe SI003AB CCD. These are arrays with 770 × 1152, 770 × 1200 and 1024 × 1024 square pixels respectively, each pixel measuring 22, 22.5 and 24 μ, which corresponds to 0.293,

* Based on observations made at Laboratório Nacional de Astrofísica/CNPq/MCT-Itajubá-Brazil. Please send offprint requests to C.H. Veiga.

** Table 1 is only available at http://www.edpsciences.org

Table 2. Normal place of Phoebe positions for each night

Number Observ.	Date Y M D	$\overline{\alpha}$ h m s	$\overline{\delta}$ ° ′ ″
03	1995 06 10.28839120	23 41 11.590	−04 11 53.39
02	1995 06 11.28233796	23 41 22.207	−04 11 00.23
09	1996 06 22.30696245	00 28 25.393	+00 32 47.85
05	1996 06 23.28531713	00 28 33.734	+00 33 24.34
02	1996 06 24.32598958	00 28 42.204	+00 34 00.79
10	1996 08 25.28588194	00 25 39.642	−00 02 14.67
08	1996 09 29.17321181	00 16 25.728	−01 04 58.67
09	1996 10 01.17351723	00 15 51.703	−01 08 36.20
05	1997 08 12.31695370	01 20 42.096	+05 41 49.55
03	1997 08 13.33337963	01 20 37.492	+05 41 03.17
01	1997 08 14.30817130	01 20 32.736	+05 40 16.02
03	1997 08 15.29278164	01 20 27.549	+05 39 26.70

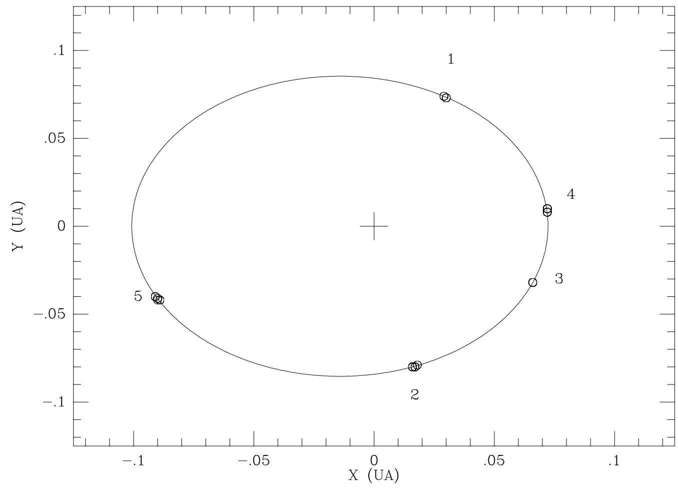

Fig. 2. Positions of the observations on Phoebe elliptic orbit. The mean dates of the observation are: 1 (06/10/1995); 2 (06/23/1996); 3 (08/25/1996); 4 (09/30/1996) and 5 (08/13/1997)

0.294 and 0.312 arcsecs/pixel on the sky. No filter was used and the exposure time varied from 30^s to 180^s, depending on the meteorological conditions. The 60 observed positions of Phoebe were taken in 12 nights distributed over 5 observational missions in the years 1995-1997. In Fig. 1 the histogram of the observations in time is presented. Each bar corresponds to an observational mission. For the mission in 1995 and the first one in 1996, Phoebe was observed at about 40^o in zenithal distance, while for the other 3 missions the observed zenithal distances were smaller than 20^o. Figure 2 presents the distribution of the observations on the orbit of Phoebe.

To find the centroids for the stars and for the satellite images the ASTROL reduction package (Colas & Serrau 1993) was used to fit a bidimensional Gaussian to the images. The centering error was typically $0\farcs01$.

3. The astrometric calibration with the USNO-A2.0 Catalog

With the publication of the USNO-A2.0 (Monet et al. 1998), we have been able to, for the first time, make the astrometric calibration of the CCD frame directly, without using secondary catalogs. The USNO-A2.0 catalogue contains more than 526 millions of stars, with magnitudes ranging between 7.5 and 21, referred to the ICRF. Its nominal position error is about $0\farcs20$. The catalogue does not include proper motions and therefore position epochs are given by the date when the plate was taken.

To do the astrometric calibration, the following procedure was employed for every CCD. Preliminarily, any star within the CCD field for which the centering error was larger than $0\farcs05$ had been removed. Then, using the measured positions for the USNO-A2.0 stars in the CCD and the corresponding catalogue positions for them, a four parameters fitting was adjusted. In this way, the position of every star measured on the CCD frame was placed on the ICRF system. As suggested by Monet et al. (1998), the step above was also attempted using locally corrected portions of the USNO-A2.0 catalogue, instead of getting the star positions directly from the catalogue. Three different approaches were used to obtain the local corrections: a simple translation by average, a first degree complete polynomial, and a third degree complete polynomial. In all cases the correction was calculated from the comparison between ACT positions, on the plates epoch, and the USNO-A2.0 catalogue entries. There was no gain in adopting the corrected USNO-A2.0 positions, and thus the original catalog positions were used throughout. Accordingly, the calculated star positions were checked against the catalog ones. Also the calculated plate scale was compared with its nominal value, being found that the difference was smaller than 2%. The calculated minus catalog residuals in equatorial coordinates were, in general, smaller than $0\farcs8$ and the standard deviations σ_x and σ_y were smaller than $0\farcs4$. For the frames where one of these values was larger than the above upper limits, a further reference star discarding procedure was adopted. Trial reductions were made removing only one of the reference stars. Therefore as many trial reductions as there were reference stars were made. The reduction in which the average residual and the standard deviations resulted largest indicated the reference star to be removed. In half of the cases this procedure was repeated two or more times, till the values fall below the upper limits.

In Fig. 3 a typical CCD frame with Phoebe is presented, to exemplify the reduction procedure. The USNO-A2.0 reference stars are marked by a circle. Those eliminated in the second fitting have cross superimposed. In this frame there were 22 USNO-A2.0 stars, at the

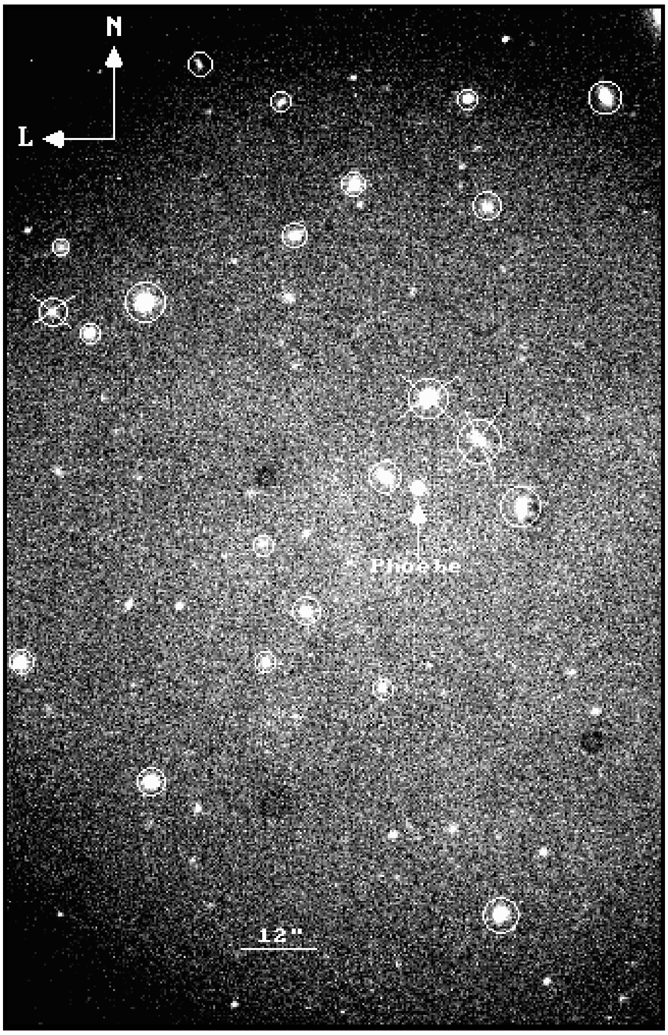

Fig. 3. CCD frame observed at 08/15/1997, $7^h0^m33^s$ UTC. Exposure time 2^m. CCD dimension 770 × 1200 square pixels

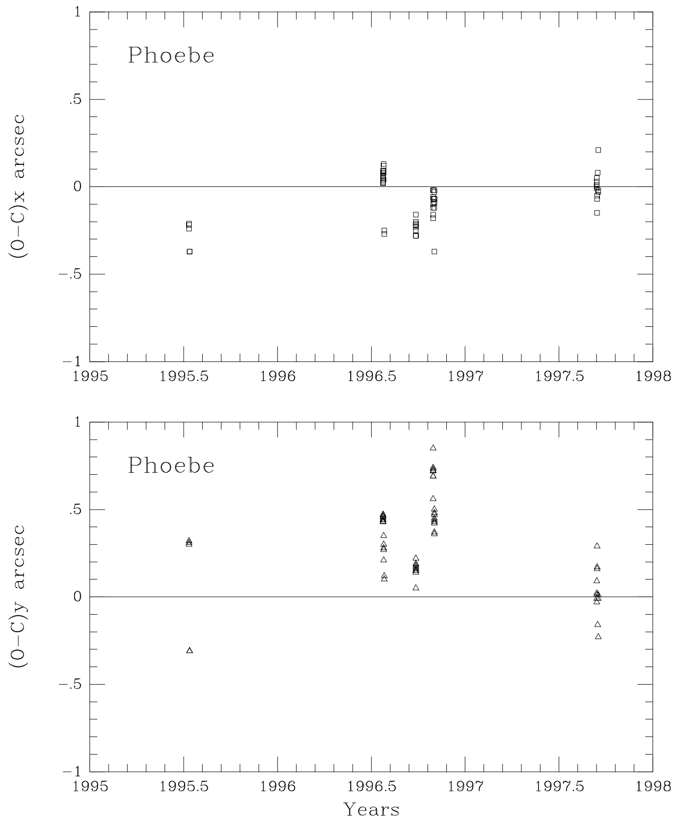

Fig. 4. Observed minus calculated residuals as function of time for Phoebe fitted observations

Table 3. Mean and standard deviation, in arcseconds, of the observed minus calculated right ascension and declination of Phoebe

	Jacobson		Bec-Borsenberger & Rocher	
	$\overline{(o-c)}_x$	$\overline{(o-c)}_y$	$\overline{(o-c)}_x$	$\overline{(o-c)}_y$
Satellite	(σ_x)	(σ_y)	(σ_x)	(σ_y)
Phoebe	−0.08	0.29	−0.07	0.37
	(0.14)	(0.26)	(0.92)	(0.33)

beginning. After the first fitting, the following values were found: $0\farcs2931$ for the plate scale, $2\farcs08$ for the largest star residual and $0\farcs229$ and $0\farcs538$ for σ_x and σ_y. Thus, to comply with the reduction criteria, further rounds of reference stars discarding were made. After the last fitting, there were 19 reference stars and the values found were: $0\farcs2932$ per pixel for the plate scale, $0\farcs70$ for the largest value of the residuals and $0\farcs234$ and $0\farcs272$ for σ_x and σ_y. The residuals for the Phoebe positions are $(-0\farcs06, 0\farcs03)$ and $(-0\farcs03, -0\farcs06)$, before and after the discarding of reference stars. Along the different observing nights for the 5 missions, Phoebe was imaged on fields of varying star density, as result the number of USNO-A2.0 varied to a large extent in different nights. The number of reference stars in each frame, used in the final reduction, ranges from 5 to 19. In Table 1 all observed positions of Phoebe are presented. The positions are referred to the ICRS, thus tied to the equator and equinox of J2000. The instants of observation are given in universal time. In Table 2 the normal places for each of the twelve nights of observations are presented.

4. Comparison between the observations and the theoretical positions

Two calculated orbits for Phoebe are considered. Those calculated by Jacobson (1998a) and Bec-Borsenberger & Rocher (1982). The comparison of our observations with the calculated positions are presented in Table 3. The mean of the observed minus calculated residuals are comparable for both the considered orbits. The larger standard deviation σ_x relatively to the Bec-Borsenberger & Rocher orbit is due to a poor fitting of the orbit which does not consider the observations made after 1981.

In Fig. 4 is presented the (O−C) distribution of the residuals between these observations and Jacobson's

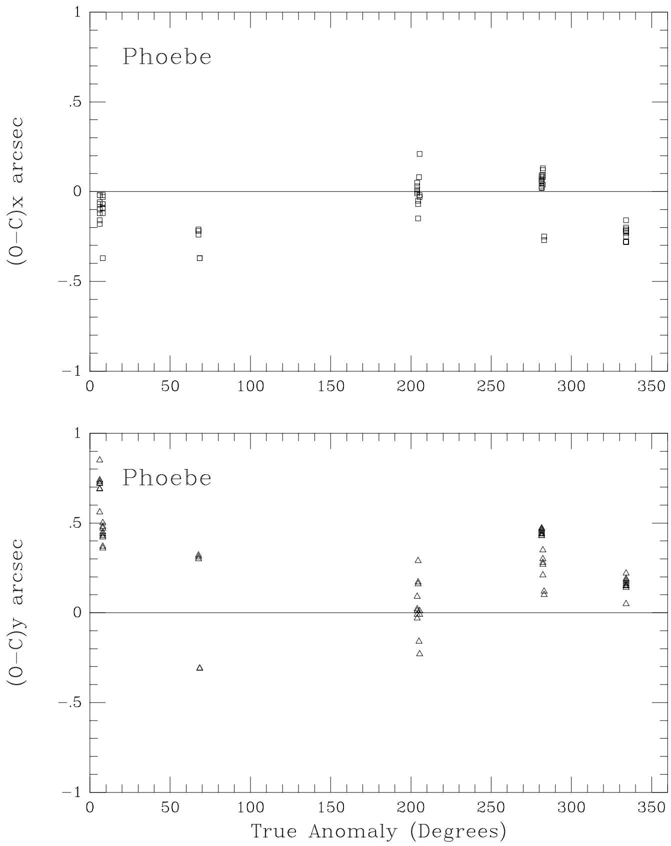

Fig. 5. The same as Fig. 4 but referred to the true anomaly

theorethical positions, with respect to the date of the observation. Figure 5 concerns the same residuals, this time relatively to the true anomaly. Comparing these figures it is noticed that the (O−C) in the y direction are clearly positive and the largest values of the residuals are reached near the periapsis.

In order to understand the bias in the y direction we compared our statistics (means and standard deviations, from Table 3) with those presented in Table 3, by Jacobson (1998b). Considering the three best fits (Wipple 1992, 1996 and Mulholland 1975, in Jacobson Table 3) it appears that the statistics in the x direction are similar and we have the same result for σ_y. However, our mean in the y direction is significantly larger.

In Fig. 4 it is seen that the main contribution for the y mean is given by two of the three missions in 1996. Furthermore, Fig. 5 shows that the set nearest to the periapsis has its residuals larger than $0''.5$, and (see histogram in Fig. 1) they contribute with more than one third for the number of 1996 observations. Therefore, this suggests that the error in the y direction come, at least partially, from a bad fit of the Phoebe orbit in the periapsis.

5. Conclusion

We presented 60 astrometric positions of Phoebe taken in 1995, 1996 and 1997 with CCD. The use of USNO-A2.0 catalogue stars to materialize the local frame on the CCD field, enabled us, for the first time, to make the astrometric calibration for a natural satellite position without using a secondary catalog.

Comparing the positions here obtained with the orbit calculated by Jacobson, the O−C residuals are alike to the best observations of Phoebe. The unusually large residuals for the observations taken near the periapsis suggest that the fit of the orbit is not good in this position. However, some new observations of Phoebe near the periapsis must be made to confirm this suggestion.

Acknowledgements. The authors wish to thank the CNPq-Brazil for partial support of this work. C.H. Veiga would like to thank State of Rio de Janeiro Science Foundation - FAPERJ for providing computational facilities for this project.

References

Bec-Borsenberger A., Rocher P., 1982, A&AS 50, 423-449
Colas F., Serrau M., 1993, Astrol and Interpol version 3.10, Édition du Bureau des Longitudes
Jacobson R.A., 1998a (personal communication)
Jacobson R.A., 1998b, A&AS 128, 7-17
Monet, et al., 1998, USNO-A V2.0 A catalog of astrometric standards, U.S. Naval Observatory
Pickering E.C., 1899, Harv. Coll. Obs. Circ. 43