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CCD astrometric observations of Saturnian satellites[⋆,⋆⋆]

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Abstract. Astrometric positions of the first eight largest Saturnian satellites and the Lagrangian satellites Helene, Telesto and Calypso are presented from 493 CCD frames taken at the oppositions in 1995 through 1999. The images were obtained over 27 nights. Observed positions are compared with the calculated ones from Vienne and Duriez TASS 1.7 for the large satellites and from JPL positions for the Lagrangian satellites. The rms is about 0″.12 for the former but 0″.20 for Iapetus and 0″.28 for Hyperion. For the Lagrangian satellites it is about 0″.21 for Helene, 2″.02 for Telesto and 0″.60 for Calypso.

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

1. Introduction

Our observations of Saturnian satellites belong to a program of systematic astrometric observations of the satellites of Jovian planets initiated in 1982 in Brazil. The results of the 138 photographic plates of the Saturnian large satellites carried out in the period 1982 to 1988 were published in Veiga & Vieira Martins (1999). For those observations the residuals give rise to a standard deviation smaller than 0″.3. Moreover 22 photographic positions of Helene with the same standard deviation where published in Veiga & Vieira Martins (2000). Also, many CCD observations made in 1995 when the Earth and the Sun crossed the plane of the Saturnian satellites were astrometrically reduced and published in Vienne et al. (2001a), here after (VTVAM). There, we presented 6006 differential positions of the eight largest satellites with dispersion smaller than 0″.15. The positions of Tethys, Dione, Rea and Titan were used to define a reference system in every frame.

In the past years some others observations of the Saturnian satellites were published, including the accurate positions presented in Peng et al. (2002). A review of the published observations and their comparison with different ephemerides can be found in Vienne (2001).

In this paper the observation of 493 CCD frames carried out during 27 nights, distributed in 10 missions in 1995–1999, are presented. The zenith distances of the planet were in general small because the telescope latitude (−23°) was close to the declination of the planet. Since the number of reference stars is very small in almost all frames, the inter-satellite reduction method as presented in (VTVAM) was used.

This paper is organized as follows: in Sect. 2 we present the observations, measurements and reduction; in Sect. 3 the observed positions are presented and compared with the calculated ones. The conclusions are presented in Sect. 4.

2. The observations, measurements and reductions

All the 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°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 in the focal plane. No filter was used. In order to avoid saturation in the CCD due to the light from the planet, a round mask was put on the CCD window and the frames were made with Saturn's image behind this mask. Since the distance from the camera window to the CCD surface is small, the penumbra region is negligible.

During the missions, 4 CCDs detectors were used. In Table 1 the characteristics of these devices are given.

Since the pixels dimension of every CCD used are about 22 μm × 22 μm, the scale per pixel is about 0″.3 × 0″.3. Therefore, the field observed with these devices is about 4′ × 5′ and 5′ × 5′.

The numbers of observed nights and useful positions in general referred to Rhea, for each satellite, are presented in Table 2. We consider as useful positions those with |O–C| smaller than 0″.5 for the eight large satellites and smaller

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[⋆] The catalog (Full Table 4) is only available in electronic form at the CDS via anonymous ftp to `cdsarc.u-strasbg.fr (130.79.128.5)` or via `http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/400/1095`

[⋆⋆] Based on observations made at Laboratório Nacional de Astrofísica/MCT-Itajubá-Brazil.

Table 1. Technical characteristics of the CCD devices. The "series" column show the Code of the series given in Table 4.

Devices	Description	Series
CCD0048	EEV P88231 (770 *X* 1152)	1-2-3-4-5-6-7-8
CCDCAM2(1)	SITe SI003AB(A1) (1024 *X* 1024)	9
CCD009	EEV-05.20.0.202 (770 *X* 1200)	10-11-12-13-14
CCDCAM2(2)	SITe SI003AB(B2) (1024 *X* 1050)	15-16

Table 2. Numbers of observed nights and useful positions in general referred to Rhea, for every satellite. We consider useful positions those with |(O−C)| smaller than 0.″5 in the case of the eight large satellites (S1–S8) and smaller than 2.″ for S12 and than 5.″ for S13 and S14.

Satellites	Positions	Nights
Mimas (S1)	329	18
Enceladus (S2)	419	23
Tethys (S3)	484	25
Dione (S4)	482	26
Titan (S6)	214	13
Iapetus (S7)	7	1
Hyperion (S8)	70	3
Helene (S12)	37	2
Telesto (S13)	24	4
Calypso (S14)	6	1

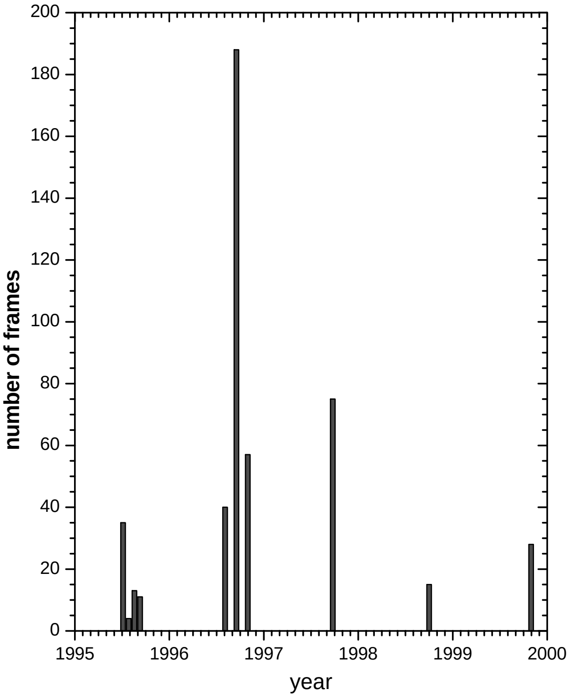

Fig. 1. Histogram of the observations with respect to time. Each bar corresponds to one mission.

Table 3. The mean, the root mean square and the standard deviation of the (O–C) (in arcseconds) for all satellites. The ephemerides compared were TASS1.7, and JPL positions for the Lagrangian satellites. The residuals are referred to S5 (if S5 is absent of the frame, we use S6, and so on with the ordering list: S5, S6, S4 and S3).

Satellite	$\overline{x}$ (rms)	$\overline{y}$ (rms)	x_σ	y_σ
Mimas	0.012 (0.134)	0.006 (0.105)	0.134	0.106
Enceladus	0.019 (0.113)	−0.027 (0.113)	0.112	0.110
Tethys	0.007 (0.111)	−0.003 (0.090)	0.111	0.090
Dione	0.014 (0.097)	−0.021 (0.091)	0.096	0.089
Titan	−0.018 (0.111)	−0.010 (0.120)	0.110	0.120
Iapetus	−0.178 (0.181)	0.084 (0.088)	0.036	0.026
Hyperion	0.191 (0.218)	0.143 (0.173)	0.105	0.099
Helene	0.119 (0.182)	0.063 (0.109)	0.139	0.089
Telesto	0.083 (1.365)	−1.177 (1.493)	1.391	0.938
Calypso	0.539 (0.552)	0.227 (0.228)	0.128	0.228

than 2.″0 for Helene and 5.″0 for Telesto and Calypso. It can be noted that the number of observations increases with the distance from Saturn. This is a consequence of the difficulty to observe faint satellites near bright planets. However, for the satellites with largest distance from the planet the number of observations decreases with the distance, mainly because the CCDs used are relatively small. In particular, Iapetus is too far from Saturn and so we have only 7 positions observed in our frames, where Saturn is always at the center of the CCD. For the very faint Lagrangian satellites we have small number of images since their observations result blurred in the neighborhood of the bright Saturn. The histogram of the number of frames with respect to the epoch of the observations is shown in Fig. 1. Each bar corresponds to one of the 10 observational missions.

As mentioned above, a round mask was put on the CCD image in order to occult the planet image. However, the ring image was saturated since the mask does not hide them. Therefore, many of the stars in the field are not see and many others are immersed in the light scattered by the planet and its rings. Furthermore, the limit magnitude of a typical image is 14. Consequently, a small number of reference stars appear and so we decided to measure only the satellite positions and adopt an inter-satellite reduction.

All frames were measured with the ASTROL software (Colas 1996), which allowed us to use a centering algorithm based on the adjustment of a point spread function. A second degree polynomial is also adjusted in order to remove the background which is affected by the light from the planet and its rings.

Table 4. Extract of the catalog.

opp.	year	*m*	day(utc)	tt-utc sec.	obs.	ref.	*t*	obj.	fl	obs1 arcsec.	obs2 (degree for C*)	*s*	*f*	o–c1 arc	o–c2 sec.	*r*	-	se	*x*pix pixel	*y*pix
118	1995	6	10.3052546	61.184	874	303	1	15	11	47.7194268	−4.1966535	2	1	0.147	−0.077	5	0	1	162.321	−13.471
118	1995	6	10.3052546	61.184	874	303	1	25	11	37.4313628	−3.7999220	2	1	0.022	−0.016	5	0	1	127.334	−12.294
118	1995	6	10.3052546	61.184	874	303	1	35	11	108.7209996	−8.5488541	2	1	−0.120	0.003	5	0	1	369.804	−27.252
118	1995	6	10.3052546	61.184	874	303	1	45	11	86.7859497	−8.0598588	2	1	−0.101	−0.057	5	0	1	295.215	−25.955
118	1995	6	10.3052546	61.184	874	303	1	65	11	−34.9822851	0.3491667	2	1	0.083	0.061	5	0	1	−118.949	0.599
118	1995	6	10.3052546	61.184	874	303	1	C5	11	61.1455158	−4.0790906	2	1	999.999	999.999	5	0	1	−208.070	12.836
118	1995	6	10.3052546	61.184	874	303	0	C*	11	355.5226507	−4.1351607	2	1	999.999	999.999	5	0	1	99 999.999	99 999.999
118	1995	6	10.3069907	61.184	874	303	1	15	11	50.4610858	−4.6822838	2	1	2.597	−0.532	5	0	1	171.656	−15.076
118	1995	6	10.3069907	61.184	874	303	1	25	11	37.5308699	−3.8116642	2	1	−0.093	−0.009	5	0	1	127.673	−12.332

For the inter-satellite reduction, we used the method presented in (VTVAM) and (Vienne et al. 2001b). More details and discussions of the method can be found in these papers.

We divided our observations in 16 series that cover one or few nights. For every series we assume that the receptor has been mounted in the same way for all the frames of the series and so the scale and the orientation remains the same for all of them. We used TASS1.7 (Vienne & Duriez 1995; Duriez & Vienne 1997) for the saturnicentric positions of the satellites. The positions of Saturn are given by the ephemerides SLP96 from the "Institut de mécanique céleste (IMCCE)" (available at `ftp://ftp.imcce.fr/pub/ephem/sun/slp96/`) found on the VSOP87 planetary theory (Bretagnon & Francou 1988), which precision is about $0\farcs4$. The frames registered and measured in pixels are not directly comparable with ephemeris, because they have been affected by some local effects. So first, we have to correct the computed coordinates with these effects due to refraction, stellar aberration, the projection of the celestial sphere on the tangential plane of the focal point, light-travel time between satellites and topocentric parallax. Comparing these apparent computed coordinates to the observed ones by a least square procedure, we deduced the scale factor and the orientation of the receptor. These two parameters are then free of these local effects. In the least square procedure, only the positions of Tethys, Dione, Rhea and Titan are used to calibrate because these satellites have the best ephemerides, and are thus probably affected by the smallest systematic effects.

The positions $(\Delta\alpha\cos\delta, \Delta\delta)$ we give in Table 4 are really astrometric ones because they are given in the J2000 system and all significant astrometric corrections have been done. But, for a given series, they are given apart from a scale factor and from a rotation. As explained in Vienne et al. (2001b), if we want to compute the astrometric coordinates in any other way, for example with other ephemerides, we have only to touch up the scale factor and the orientation of the receptor.

3. Observed positions and comparison with the theory

As mentioned above, the observations were compared with TASS1.7 for the eight large satellites. If the |O−C| for one observation was larger than $0\farcs5$, it was rejected. For the Lagrangian satellites, the JPL calculated positions (Jacobson 2001) was used and if the |O−C| was larger than $2\farcs0$ for Helene and larger than $5\farcs0$ for Telesto and Calypso it was rejected. We chose the above limits since the residuals out of these intervals are evidently outliers.

The (O–C) statistics are presented in Table 3 and Fig. 2 shows the corresponding histograms. We can observe that the largest residuals appear for Mimas in the x direction, which is explained by the difficulty of taking measurements of the center of the satellite image within a region where light scattered by the rings is very significant. The mean values for the Lagrangian satellites are very large. Besides intrinsic errors brought about by the faintness of the images, this suggests that the theoretical positions of these satellites are not very good. For Iapetus and Hyperion, the means are also large. However the means for these satellites in (VTVAM) are smaller. Probably this is a consequence of the poor quality of our images of these relatively faint satellites.

The catalog of our astrometric data is available in electronic form at CDS via anonymous ftp to `cdsarc.u-strasbg.fr` or via `http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/400/1095`. It is also available at `ftp://ftp.bdl.fr/pub/NSDC/saturn/raw_data/position/`. It contains astrometric coordinates, in the J2000 system, of the observations analyzed in this section. Table 4 shows an extract. It contains satellite/satellite positions expressed in arcseconds, gathered by series with the corresponding scale (in pixels/arcsec) and orientation (in radians). The dates correspond to the mid-time of the exposure. The date is not light-time corrected. In this catalog the positions with large residuals are also presented. so we have 2183 positions of Saturnian satellites but only 2072 of these positions are in the intervals defined in the other tables above.

The format and the conventions of our catalog are almost the same presented in (VTVAM) and quite similar to the one by Strugnell and Taylor (1990). In a FORTRAN code, lines are read with the format: (i3, i5, i3, f11.7, f7.3, 2i4, i2, 1x, a2, a1, i2, i1, 2(1x, f13.7), 2i2, 2(ix, f7.3), 3i3, 2f10.3). The meaning of each parameter can be found in Strugnell & Taylor (1990) and in (VTVAM), however here some are slightly different.

- opp.: opposition number, 1 = 1874 to 122 = 1999.
- year, *m*, utc: year, month and utc date of the observation (like VTVAM).

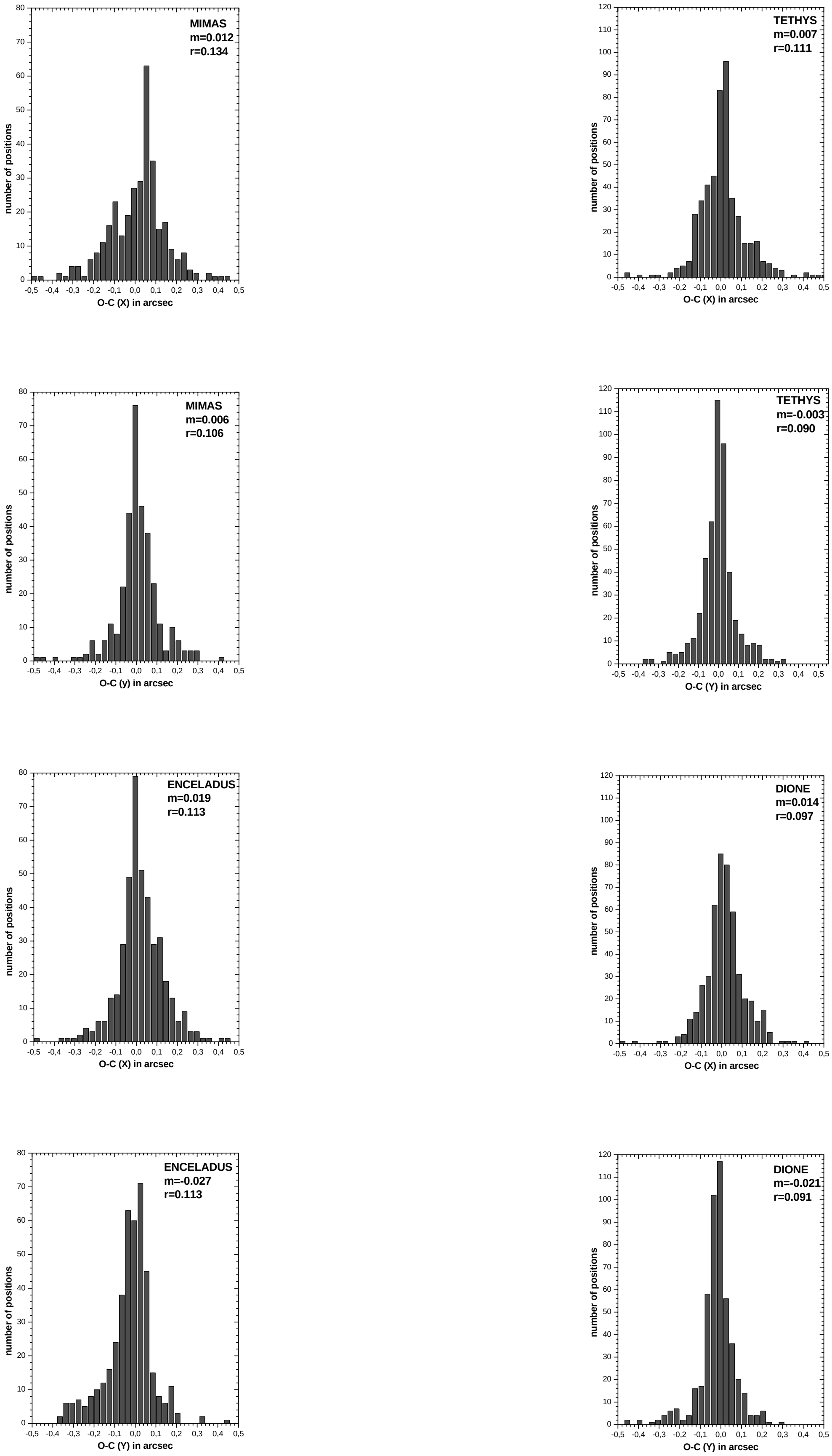

Fig. 2. Histogram for the $\Delta\alpha \cos\delta(X)$ and $\Delta\delta(Y)$ residuals of the observed satellites.

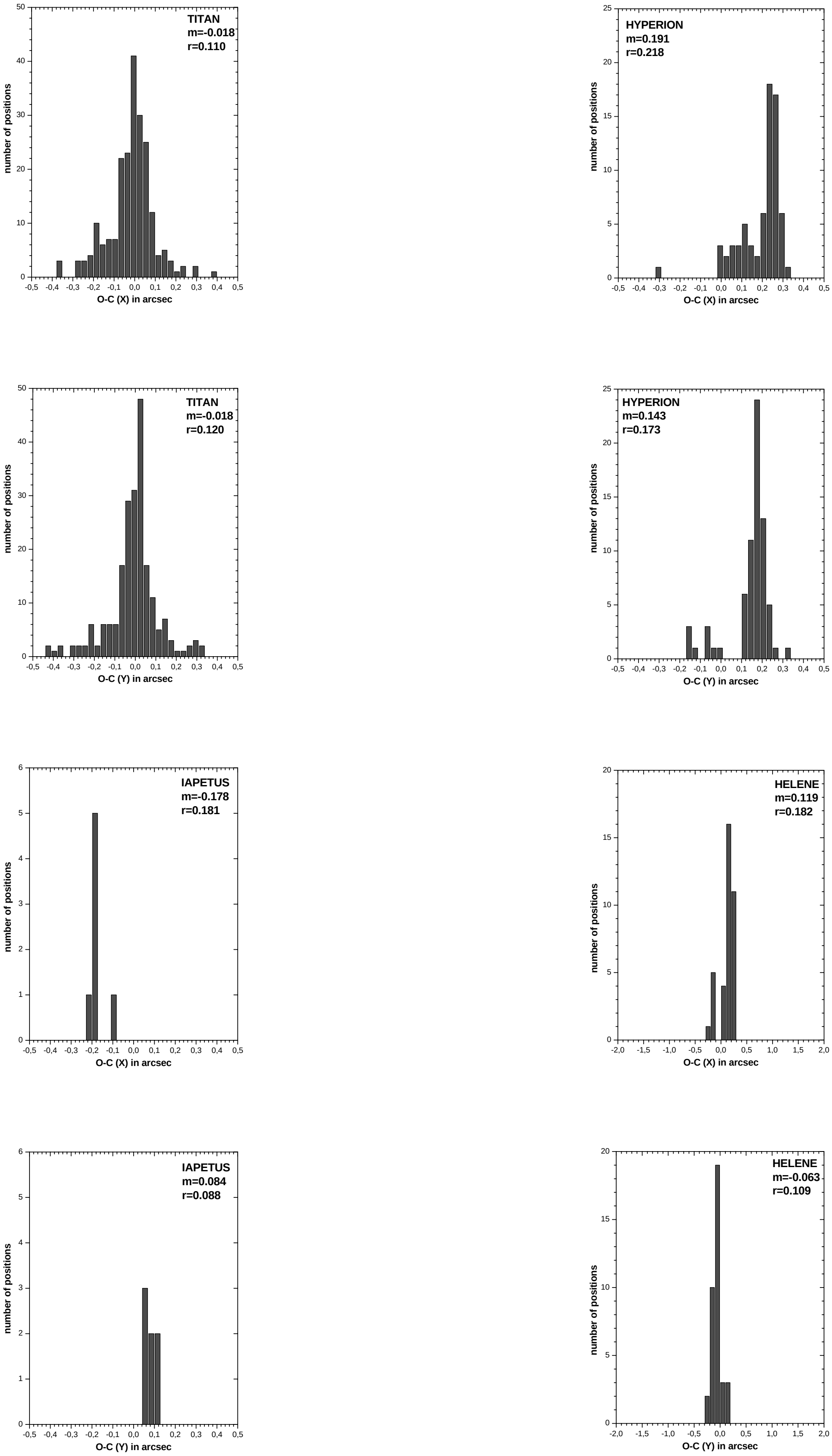

Fig. 2. continued.

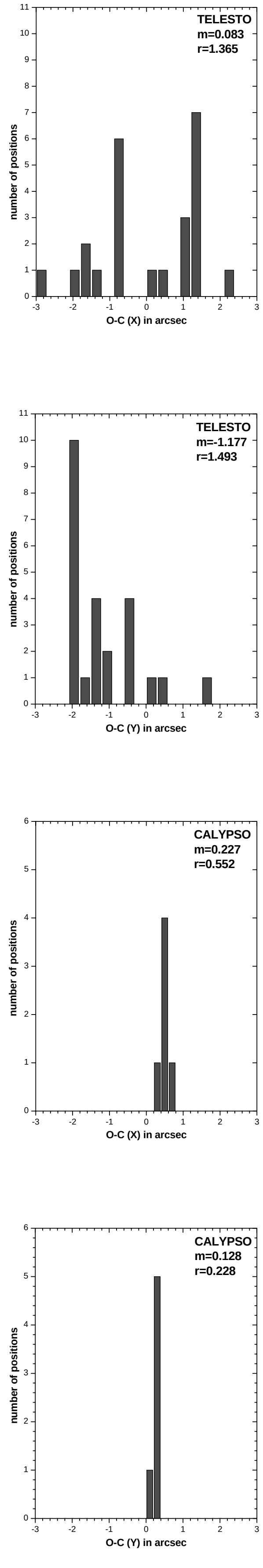

Fig. 2. continued.

- tt-utc: TT-UTC in seconds (like VTVAM).
- obs.: IAU observatory code from the Minor Planet Center.
- reference code catalog (we have chosen 303 for the present observations).
- *t.*: observation type. 0 = α, δ , 1 = $\Delta\alpha\cos\delta, \Delta\delta$, 2 = $\Delta\alpha, \Delta\delta$, 3 = position angle, separation .
- obj.: subject satellite, reference satellite. 0 for Saturn, 1 to 8 for S1 to S8, 12 for Helene, 13 for Telesto, 14 for Calypso, C for the center of the plate which is not a physical object.
- fl.: flags of presence of the first and second coordinates.
- obs1, obs2: first and second coordinates. It is 0 when the coordinate is not present, see fl.
- *s*: reference system. 0 = mean equator and equinox B1950, 1 = true equator and equinox of date of observation, 2 = mean equator and equinox of J2000.
- *f*: reference frame. 0 = topocentric, 1 = geocentric, 2 = heliocentric.
- o–c1, o–c2: residuals of observations in arcsecond computed with TASS1.7, it is 999.999 when the residuals are not computed and it is 888.888 when the residuals are greater than 100 in absolute value.
- *r*: the number of the satellite used as reference in the computation of O–C.
- -: 0 for no meaning and 1 when the frame was not used in the computation of the scale and the direction of the series (see se column).
- se: the number of the series, the scale and orientation are the same for all observations of one series.
- *x*pix, *y*pix: original coordinates in pixels.

We add at the end of our catalog some lines which indicate how the reductions have been done and which corrections have been applied to get the coordinates. In particular, we give the scale and the orientation of each series of observations. Note that the orientation refers to the true equator of the date because the calibration parameters are issued from the direct comparison between the observed frame and a "computed frame". But, as explained in (VTVAM) (see also Vienne et al. 2001b), it is possible to adjust the scale and the orientation directly by comparing the observed astrometric coordinates and the computed ones.

4. Conclusion

We present 2005 positions of the main satellites of Saturn and 67 positions of the Lagrangian satellites from CCD observations in 1995–1999 in Brazil. Since most of these frames have no reference stars, we applied an inter-satellite reduction. The positions of Tethys, Dione, Rhea and Titan given by TASS1.7 were used to determine the scale factor and the orientation of the receptor.

The comparison of the observed and computed positions shows that the RMS is about $0\farcs12$ for the main satellites and larger for Hyperion and the Lagrangian satellites. The coordinates are given in NSDC base data and presented apart from the scale factor and from rotation, but all astrometric corrections are done. So, these differential positions are really absolute ones in the meaning that no astrometric correction is necessary to use them, even if one wants to adjust the calibration.

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