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Astrometric positions for 18 irregular satellites of giant planets from 23 years of observations[⋆,⋆⋆]

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ABSTRACT

Context. The irregular satellites of the giant planets are believed to have been captured during the evolution of the solar system. Knowing their physical parameters, such as size, density and albedo is important to constrain from where they come and how they were captured. The best techniques to obtain this parameters are observations in loco by spacecrafts or stellar occultations by the objects. Both techniques demand great precision.
Aims. We aimed to reduce more than one hundred thousand observations made in three sites (Observatório do Pico dos Dias, Observatoire de Haute Provence and European Southern Observatory - La Silla) between 1992 and 2014 to obtain good positions for the irregular satellites to improve their ephemeris.
Methods. We used the software PRAIA (Platform for Reduction of Astronomical Images Automatically) to make the astrometric reduction. The UCAC4 catalogue represented the International Celestial Reference System in the reduction of the CCD frames. The ephemeris generated by the kernels from SPICE/JPL was used to identify the positions of the satellites in the frames. Some procedures were taken to overcome missing or incomplete information (coordinates, date), mostly in the older images of the OPD database.
Results. We managed to obtain more than 6000 positions for 18 irregular satellites, being 12 for Jupiter, 4 for Saturn, 1 for Uranus and 1 for Neptune. For some satellites the number of positions is bigger than 50% of the number used in earlier orbital numerical integrations
Conclusions. Comparison of our positions with recent JPL ephemeris suggests the presence of systematic errors in the orbits of at least a few irregular satellites. The most evident case was an error in the inclination of Carme.

Key words. Irregular Satellites

1. Introduction

The irregular satellites of the giant planets are smaller than the regular ones with more eccentric, inclined, distant and, in most cases, retrograde orbits. Due to their orbital configurations, it's largely accepted that these objects were captured in the early solar system (Sheppard & Jewitt 2003).

The majority of these objects was discovery in the last decade [1] mainly because they are faint objects. They were never visited by a spacecraft, with the exception of Phoebe, in a flyby by the Cassini space probe in 2004 (Desmars et al. 2013).

There are some hypotheses about the capture methods of objects by Giant Planets. These are the Gas Drag in the primordial circumplanetary nebulae (Sheppard 2006) where the object would be affected by the gas drag and its velocity slowed until being captured by the planet. Another hypotheses is called pull-down capture (Sheppard 2006), where the mass of the planet would increases while the object where temporarily captured.

A hypotheses, based in the Nice model (Morbidelli et al. 2005; Tsiganis et al. 2005; Gomes et al. 2005), was proposed by Nesvorný et al. 2007 and, in the specific case of Jupiter with the modern Nice model, by Nesvorný et al. 2014. During the early solar system instability, encounters between the outer planets occurred. These planetary encounters could exchange energy and angular momentum between planets and the objects nearby making it possible for the capture of irregular moons by the giant planets. In this model, the survival rate of prior-LHB (Late Heavy Bombardment) satellites is very small.

Another important model is the capture through collisional interactions (Sheppard 2006). A collision between two small bodies in the Hill's sphere of the planet could generate fragmented objects and the dissipated energy could be such a way that some of these objects could be captured.

Some of these objects are in dynamical groups with similar orbital elements, called families, similar to families

Send offprint requests to: A. R. Gomes-Júnior
⋆ Based on observations made at Laboratório Nacional de Astrofísica (LNA), Itajubá-MG, Brazil.
⋆⋆ Partially based on observations through the ESO runs 079.A-9202(A), 075.C-0154, 077.C-0283 and 079.C-0345.
[1] Website: http://ssd.jpl.nasa.gov/?sat_discovery

found in the main belt of asteroids. These families may have been created by a parent body disrupted by collisions with comets or other satellites (Nesvorný et al. 2004). Collisions with comets are more likely to have occurred during the Late Heavy Bombardment (LHB) (Gomes et al. 2005).

Nesvorný et al. 2003 studied the collision rates between irregular satellites and concluded that some satellites could have been removed by collision with a bigger satellite. The rate collision between satellites of the Himalia Group (Himalia, Elara, Lysithea and Leda, mainly), for instance, was found to be more than 1 during the solar system age suggesting that their current structure was originated by satellite-satellite collision.

For Phoebe, ejected material from its surface caused by impacts could evolve due to Poynting-Robertson drag and collide with Iapetus causing the large variation in albedo observed on it (Nesvorný et al. 2003). Indeed, Cassini was able to detected in Phoebe an absorption feature at 2.42 μm (probably CN combinations) that was also detected in the dark side of Iapetus (Clark et al. 2005).

If these objects were captured, there remains the question of where do they come from. Clark et al. 2005 showed from imaging spectroscopy from Cassini that Phoebe has a surface probably covered by material from the outer solar system and Grav et al. 2003 showed that the satellites of the Jovian Prograde Group Himalia have grey colors implying that their surfaces are similar to that of C-type asteroids. In this same work, the Jovian Retrograde Group Carme was found to have surface colors similar to the D-type asteroids like Hilda or Trojan families while JXIII Kalyke has a redder color like Centaurs or trans-neptunian objects (TNOs).

For Saturnian satellites, Grav & Bauer 2007 showed by their colors and spectral slopes that these satellites contain a more or less equal fraction of C-, P- and D-like objects but SXXII Ijiraq is marginally redder than D-type objects. These works may suggest different origins for the irregular satellites.

In this context, we used 3 databases for deriving precise positions for the irregular satellites observed at Observatório do Pico dos Dias (1.6 m and 0.6 m telescopes, IAU code 874), Observatoire Haute-Provence (1.2m telescope, IAU code 511) and ESO (2.2 m telescope, IAU code 809). More than 100 thousand images were obtained for a variety of observational programs. In particular, many irregular satellites were observed between 1992 and 2014 covering a few orbital periods of these objects (12 satellites of Jupiter, 4 of Saturn, Sycorax of Uranus and Nereid of Neptune). The positions derived from the observations can be used in new numerical integrations, generating more precise ephemerides. Stellar occultations by these satellites could then be better predicted. Once observed, they will make it possible to obtain the satellites' physical parameters (shape, size, albedo, density) with unprecedented precision.

The observations are described in Sect. 2. The astrometric procedures in Sect. 3. The obtained positions are presented in Sect 4 and analysed in Sect. 5. Conclusions are given in Sect. 6.

2. Observations

Our database consisted in optical images from many observational programs performed with different telescopes/detectors targeting a variety of objects, among which irregular satellites. The observations come from 3 sites: Observatório do Pico dos Dias (OPD), Observatoire Haute-Provence (OHP) and European Southern Observatory (ESO). Altogether there are more than 100 thousand FITS images obtained in a large time span (1992-2014). Since the OHP and mostly the OPD databases were not well organized, we had to developed an automatic procedure to identify and filter only the images of interest, that is, of the irregular satellites. The instruments and images characteristics are described in the following subsections.

2.1. OPD

The OPD database was produced at Observatório do Pico dos Dias (OPD, IAU code 874)[2], located at geographical longitude $+45° \, 34' \, 57''$, latitude $-22° \, 32' \, 04''$ and an altitude of 1864 m, in Brazil. More than 100 thousand images were observed in 615 nights (244 with Perkin-Elmer, 319 with Boller & Chivens and 52 with Zeiss) between 1992 and 2014 by our group. In Fig 1 we plot the quantity of frames obtained by satellite over time and in Fig 2 the number of frames by satellite for each telescope. Two telescopes of 0.6 m diameter (Zeiss and Boller & Chivens) and one 1.6 m diameter (Perkin-Elmer) were used for the observations. It was identified 5248 observations containing irregular satellites, being 3168 in Boller & Chivens, 1967 en Perkin-Elmer and 113 in Zeiss.

This is a inhomogeneous database with observations made with 9 different detectors (see Table 1) and 6 different filters. The headers of most of the older FITS images had missing, incomplete or incorrect coordinates or date. In some cases, we could not identify the detector origin. The procedures used to overcome these problems are described in Sect. 3.

Table 1. Characteristics of OPD detectors used in this work.

Perkin-Elmer		
Detector	Field of View (arcmin)	Pixel Scale ("/px)
CCD009	1.8 x 2.8	0.293
CCD048	3.8 x 5.6	0.293
CCD101	5.3 x 5.3	0.312
CCD105	6.0 x 6.0	0.176
CCD106	5.3 x 5.3	0.312
IKON	6.0 x 6.0	0.176
IXON	3.0 x 3.0	0.176
Boller & Chivens		
Detector	Field of View (arcmin)	Pixel Scale ("/px)
CCD009	3.6 x 5.4	0.569
CCD048	7.4 x 11.1	0.577
CCD098	11.8 x 11.8	0.346
CCD101	10.5 x 10.5	0.616
CCD105	10.9 x 10.9	0.319
CCD106	10.5 x 10.5	0.616
IKON	11.7 x 11.7	0.342
IXON	5.8 x 5.8	0.342
Zeiss		
Detector	Field of View (arcmin)	Pixel Scale ("/px)
CCD009	3.6 x 5.3	0.570
CCD654	3.6 x 2.7	0.571
CCD105	11.8 x 11.8	0.347
CCD106	10.6 x 10.6	0.620
IKON	11.9 x 11.9	0.348

[2] Website: http://www.lna.br/opd/opd.html - in Portuguese

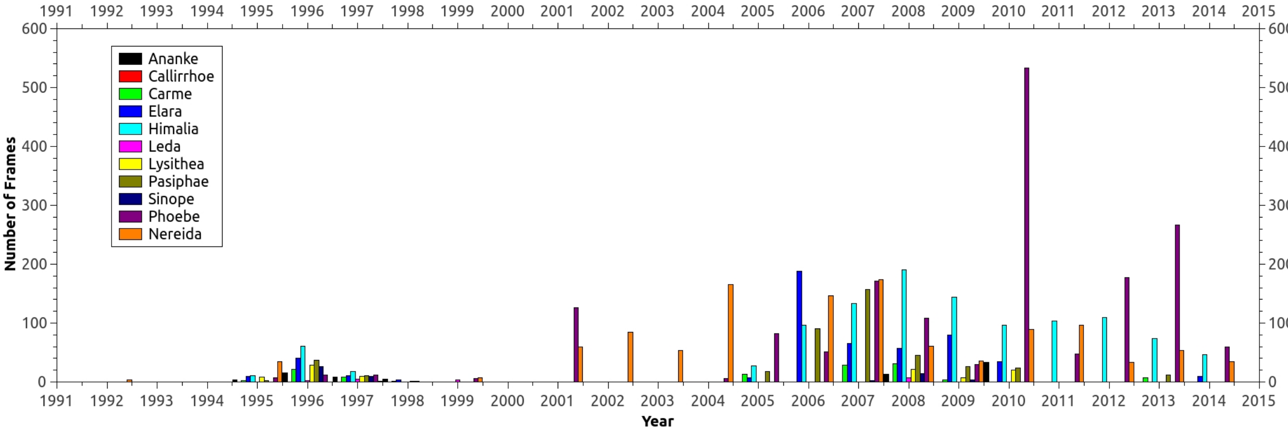


Fig. 1. Distribution of observations of the satellites over time at OPD.

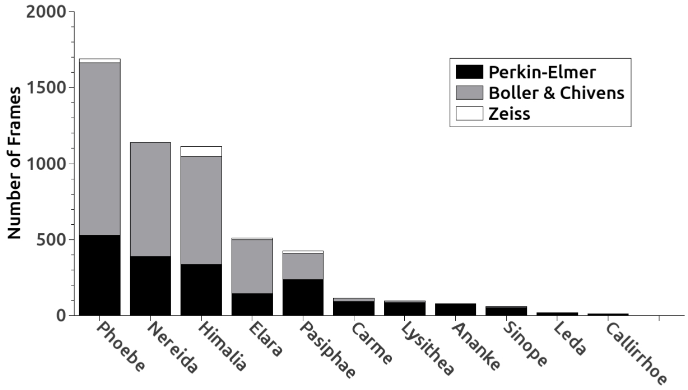


Fig. 2. Number of frames observed by satellite by OPD telescope.

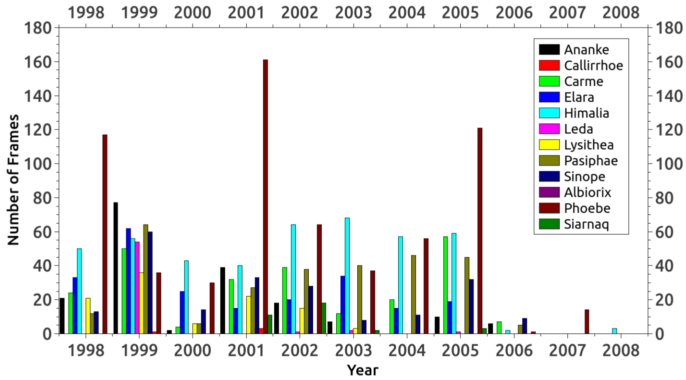


Fig. 3. Distribution of the observations of the satellites over time from observations at OHP.

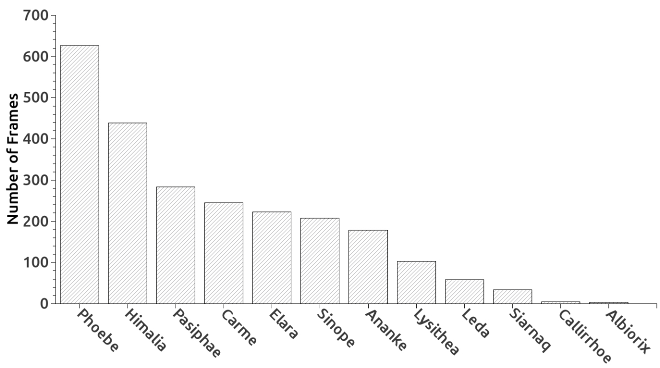


Fig. 4. Number of frames observed by satellite observed at OHP.

2.2. OHP

The instrument used at the Observatoire de Haute Provence (OHP, IAU code 511, 5° 42′ 56.5″ E, 43° 55′ 54.7″N, 633.9 m) was the 1.2m-telescope in a Newton configuration. The focal length is 7.2 m. This database contains more than 20 thousand images obtained in 355 nights between 1997 and 2008. During this time only one CCD detector 1024×1024 was used. The size of field is $12' \times 12'$ with a pixel scale of 0.69″. All the images were acquired without the use of filters. Fig. 3 shows the Distribution of the observation of the satellites over time and Fig. 4 the number of frames observed for each satellite. From this observations, 2408 was identified containing irregular satellites.

2.3. ESO

Observations were made at the 2.2 m Max-Planck ESO (ESO2p2) telescope (IAU code 809) with the Wide Field Imager (WFI) CCD mosaic detector. Each mosaic is composed by eight CCDs of $7.5' \times 15'$ (RA, Dec) size, resulting in a total coverage of $30' \times 30'$ per mosaic. Each CCD has $4k \times 2k$ pixel with a pixel scale of 0.238″. The filter used was a broad-band R filter (ESO#844) with $\lambda_c = 651.725$ nm and $\Delta\lambda = 162.184$ nm. The telescope was shifted between exposures in such a way that each satellite was observed at least twice in different CCDs.

The satellites were observed in 24 nights, divided in 5 missions, between April 2007 and May 2009 during the program that observed stars along the sky path of trans-neptunian objects (TNOs) to identify candidates to stellar occultation as presented in Assafin et al. (2012). It was identified in the mosaics 810 observations containing irregular satellites.

3. Astrometry

Almost all the frames were photometrically calibrated with auxiliary bias and flat-field frames by means of standard procedures using IRAF[3] and, for the mosaics, using the esowfi (Jones & Valdes 2000) and mscred (Valdes 1998) packages. Some of the nights at OPD didn't have bias and flat-field images so the correction was not made.

The astrometric reductions were made by the use of the Platform for Reduction of Astronomical Images Automatically (PRAIA) (Assafin et al. 2011). The (x, y) measurements were performed with 2-dimensional circular symmetric Gaussian fits within 1 Full Width Half Maximum (FWHM = seeing). Within 1 FWHM, the image profile is well described by a Gaussian profile, free from the wing distortions, which jeopardize the center determination. PRAIA automatically recognizes catalog stars and determines (α, δ) with a number of models relating the (x, y) measured and (X, Y) standard coordinates projected in the sky tangent plane.

We used the UCAC4 (Zacharias et al. 2013) as the practical representative of the International Celestial Reference System (ICRS). For OPD and OHP, we used the six constants polynomial to model the (x, y) measurements to the (X, Y) tangent plane coordinates as for ESO we also used a 3rd degree polynomial to combine positions of stars in different CCDs and mosaics. To help identifying the satellites in the frames, and derive the ephemeris for the instants of the observations for comparisons (see Sect 5), we used the kernels from SPICE/JPL[4]. The JPL ephemeris that represented the Jovian satellites was the DE421 + JUP300. For the Saturnian satellites the ephemeris was DE421 + SAT359 to Hyperion, Iapetus and Phoebe and DE421 + SAT361 to Albiorix, Siarnaq and Paaliaq. The DE421 + URA095 was used for Sycorax and DE421 + NEP081 for Nereid.

In the OPD database, there were some images (mostly the older ones) with missing coordinates or wrong date in their headers. In the case of missing or wrong coordinates, we adopted the ephemeris as the central coordinates of the frames. Even for objects in the corner, this is enough for PRAIA to correctly identify the stars and satellites in the FOV. When the time wasn't correct, the FOV identification crashed. In this case, a search for wrong date (year) displaying was performed. Problems like registering local time instead of UTC were also identified and corrected.

For the ESO images, first the astrometry of the individual CCDs was performed and the (x, y) measurements were corrected by the field distortions patterns determined by Assafin et al. (2012). Finally, all positions coming from different CCds and mosaics were combined to produce a global solution for each night and field observed, and final (α, δ) object positions were obtained in the UCAC4 system.

For each night a sigma-clipping procedure was performed to eliminate discrepant positions (outliers). A threshold of 120 mas and 2.5 sigma was adopted.

In Table 2 we list the mean error in α and δ for the reference stars obtained by telescope.

From Table 3 to 7 we list the dispersion of the offsets in α and δ obtained by telescope for each satellite. The final number of frames, number of nights and the mean number of UCAC4 stars used in the reduction are also given.

[3] Website: http://iraf.noao.edu/
[4] Website: http://naif.jpl.nasa.gov/naif/toolkit.html

Table 2. Astrometric (α, δ) reduction by telescope.

Telescope	Mean errors σ_α mas	σ_δ mas	UCAC4 stars
Perkin-Elmer(OPD)	51	48	24
Boller & Chivens (OPD)	56	55	36
Zeiss (OPD)	58	57	95
OHP	50	49	46
ESO	26	25	632

Mean errors are the standard deviations in the (O−C) residuals from (α, δ) reductions with the UCAC4 catalog.

Table 3. Astrometric (α, δ) reduction for each satellite observed with the Perkin-Elmer telescope.

Perkin-Elmer					
Satellite	Mean errors σ_α mas	σ_δ mas	Nr frames	Nr nights	UCAC4 stars
Ananke	93.9	185.7	52	7	40
Callirrhoe	66.6	35.4	9	1	3
Carme	97.0	94.3	68	7	49
Elara	230.8	118.7	99	12	32
Himalia	290.5	45.4	238	18	37
Leda	207.4	79.0	6	6	46
Lysithea	107.0	79.4	53	8	41
Pasiphae	157.0	92.5	144	13	22
Sinope	155.0	77.3	37	8	42
Phoebe	73.7	95.3	410	22	6
Nereid	200.3	142.5	289	29	8

Mean errors are the standard deviations in the offsets from (α, δ) reductions with the UCAC4 catalog.

Table 4. Astrometric (α, δ) reduction for each satellite observed with the Boller & Chivens telescope.

Boller & Chivens					
Satellite	Mean errors σ_α mas	σ_δ mas	Nr frames	Nr nights	UCAC4 stars
Carme	68.5	111.4	22	4	45
Elara	55.4	43.0	294	23	53
Himalia	83.2	43.2	560	31	57
Lysithea	23.6	42.7	7	2	60
Pasiphae	128.5	71.1	140	14	57
Sinope	59.7	17.3	4	1	22
Phoebe	43.8	48.4	810	42	17
Nereid	61.0	45.6	514	38	20

Table 5. Astrometric (α, δ) reduction for each satellite observed with the Zeiss telescope.

Zeiss					
Satellite	Mean errors σ_α mas	σ_δ mas	Nr frames	Nr nights	UCAC4 stars
Elara	17.5	21.4	10	1	146
Himalia	112.4	72.3	56	4	91
Pasiphae	24.6	25.1	11	1	140
Phoebe	37.2	30.6	19	1	16

Table 6. Astrometric (α, δ) reduction for each satellite observed with the OHP telescope.

OHP					
Satellite	Mean errors σ_α mas	σ_δ mas	Nr frames	Nr nights	UCAC4 stars
Ananke	100.6	89.0	141	20	62
Carme	114.9	96.3	204	29	39
Elara	52.0	61.2	187	25	37
Himalia	49.6	66.6	357	43	49
Leda	118.8	33.1	48	7	14
Lysithea	63.0	50.8	84	13	56
Pasiphae	101.0	75.9	248	32	39
Sinope	196.1	73.4	169	25	43
Phoebe	30.5	31.9	516	63	51
Siarnaq	46.5	98.4	20	6	32

Table 7. Astrometric (α, δ) reduction for each satellite observed with the ESO telescope.

ESO					
Satellite	Mean errors σ_α mas	σ_δ mas	Nr frames	Nr nights	UCAC4 stars
Ananke	225.4	19.1	57	3	761
Callirrhoe	29.1	33.9	16	1	493
Carme	140.4	110.8	37	4	1074
Elara	112.2	87.9	46	4	1492
Himalia	76.7	74.1	23	2	1153
Leda	60.3	125.5	44	3	632
Lysithea	76.4	88.4	90	6	695
Megaclite	52.7	34.9	10	1	445
Pasiphae	70.6	114.8	66	5	836
Praxidike	7.8	38.2	2	1	1934
Sinope	339.1	70.2	11	2	1542
Themisto	894.1	28.5	16	2	1232
Albiorix	76.0	50.9	46	6	330
Paaliaq	301.4	59.0	11	4	382
Phoebe	102.1	57.9	32	5	312
Siarnaq	86.2	66.3	56	6	283
Sycorax	150.7	82.2	35	9	375
Nereid	115.4	78.5	99	12	362

4. Satellite Positions

The catalog of positions of the satellites consists in 6523 positions observed between 1992 and 2014 for 12 satellites from Jupiter, 4 from Saturn, 1 from Uranus and 1 for Neptune. The positions in this catalog are in the ICRS (J2000) and have the mean epoch of observations, the position error in the mean epoch of observations, filters used, magnitudes and magnitude errors estimates. These positions are freely available in electronic form at the CDS.

5. Comparison with current ephemeris

Intending to see the potential of our results to improve the ephemeris of the irregular satellites observed, we analysed the offsets of our positions related to the ephemeris mentioned at Sect. 3. In Fig. 5 we plot the mean offsets for each night and their dispersions (1 sigma error bars) as a function of the true anomaly in right ascension (5a) and declination (5b). Fig. 5b clearly shows us a systematic error in declination. When Carme is close to its apojove (true anomaly = 180°) its offsets are more likely to be more negative than those close to its perijove (true anomaly = 0°). The offsets obtained observations by 4 telescopes using different cameras and filters are in good agreement, meaning that this is an error in the ephemeris.

For this reason, we conclude there is an error in the inclination of the orbit of Carme. This pattern was also seen for other satellites like Ananke and Pasiphae. For some satellites, the orbital coverage is not enough to clearly indicate the presence of systematic errors in the orbital elements.

Table 8. Comparison of positions obtained with Jacobson et al. 2012.

	Number of Positions				
Satellite	OPD	OHP	ESO	Total	Jacobson
Ananke	52	141	57	250	600
Callirrhoe	9	-	20	29	95
Carme	90	204	37	331	973
Elara	403	187	46	636	1115
Himalia	854	357	23	1234	1757
Leda	6	48	44	98	178
Lysithea	60	84	90	234	431
Megaclite	-	-	10	10	50
Pasiphae	295	248	66	609	1629
Praxidike	-	-	2	2	59
Sinope	41	169	11	221	854
Themisto	-	-	16	16	55
Albiorix	-	-	46	50	137
Paaliaq	-	-	11	11	82
Phoebe	1239	516	32	1787	3479
Siarnaq	-	20	56	76	239
Sycorax	-	-	35	35	237
Nereid	803	-	99	902	716

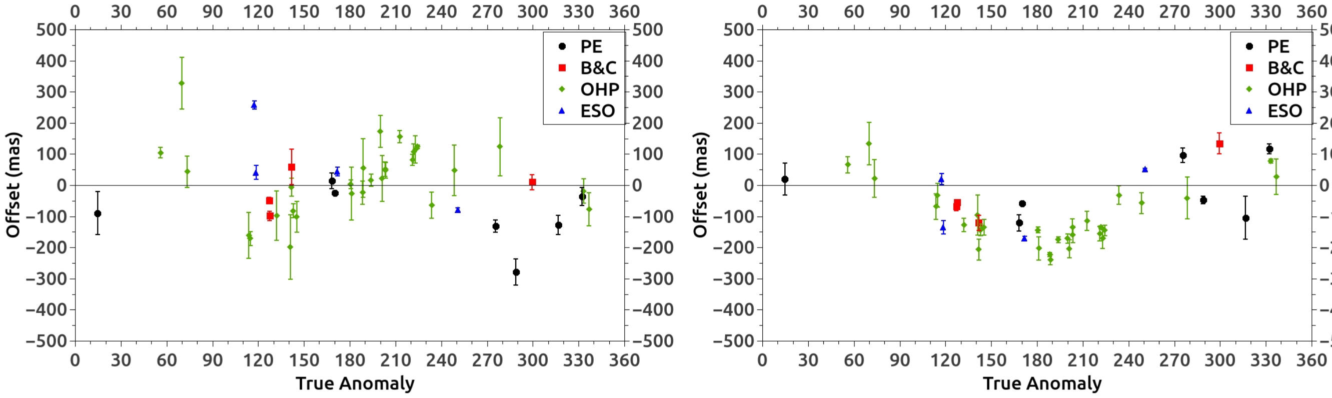
Comparison between the number of positions obtained in our work with the number used in the numerical integration as published by Jacobson et al. 2012.

6. Conclusions

The positions of all the objects were determined using the PRAIA package. The package was suited to cope with the huge amount of observations and the task of identifying the satellites within the database. PRAIA tasks were also useful to deal with the missing or incorrect coordinate and time stamps present mostly in the old observations. The UCAC4 was used as the reference frame.

We managed a large database with more than 100 thousand FITS images acquired by 5 telescopes in 3 sites between 1992 and 2014. From that, we identified 8466 observations of irregular satellites, from which we managed to obtain 6523 positions, giving a total of 3666 positions for 12 satellites of Jupiter, 1920 positions for 4 satellites of Saturn, 35 positions for Sycorax (Uranus) and 902 positions for Nereid (Neptune).

For some satellites the number is comparable to the number used in the numerical integration of JPL ephemeris (Jacobson et al. 2012) (See Table 8). And systematic errors in the ephemeris were found for some satellites.



(a) Right Ascension

(b) Declination

Fig. 5. Mean Offset and dispersion (1 sigma error bars) in the coordinates of Carme taken night by night by true anomaly.

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