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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 where they came from and how they were captured. The best way to obtain these parameters are observations in loco by spacecrafts or from stellar occultations by the objects. Both techniques demand that the orbits are well known.

Aims. We aimed to obtain good astrometric positions of irregular satellites in order to improve their orbits and ephemeris.

Methods. We identified and reduced observations of several irregular satellites from a database of more than one hundred thousan images obtained between 1992 and 2014 at three sites (Observatório do Pico dos Dias, Observatoire de Haute-Provence and European Southern Observatory - La Silla). We used the software PRAIA (Platform for Reduction of Astronomical Images Automatically) to make the astrometric reduction of the CCD frames. The UCAC4 catalogue represented the International Celestial Reference System in the reductions. The identification of the satellites in the frames was done through their ephemerides as determined from the SPICE/NAIF kernels. Some procedures were taken to overcome missing or incomplete information (coordinates, date), mostly for the older images.

Results. We managed to obtain more than 6000 positions for 18 irregular satellites, being 12 for Jupiter, 4 for Saturn, 1 for Uranus (Sycorax) and 1 for Neptune (Nereid). For some satellites the number of obtained positions is more than 50% of that 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. Planets and satellites: general - Astrometry: individual: Jovian and Saturnian 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] only 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. There is 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 increase while the object was 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.

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⋆ The complete version of Table 8 is only available through CDS.

⋆⋆ 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.

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[1] Website: http://ssd.jpl.nasa.gov/?sat_discovery

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 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 they came 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 that 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). 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 CCD 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. The observations were made between 1992 and 2014 by our group in a variety of observational programs. In Fig 1 we plot the number 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 in Perkin-Elmer and 113 in Zeiss.

This is an 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)
CCD048	770 x 1152	22.5
CCD098	2048 x 2048	13.5
CCD101	1024 x 1024	24.0
CCD105	2048 x 2048	13.5
CCD106	1024 x 1024	24.0
CCD301	385 x 578	22.0
CCD523	455 x 512	19.0
IKON	2048 x 2048	13.5
IXON	1024 x 1024	13.5

The plate scale of the telescopes are 13.09"/mm for Perkin-Elmer, 25.09"/mm for Boller & Chivens and 27.5"/mm for Zeiss.

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. The observations were made between 1997 and 2008. During this time only one CCD detector

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

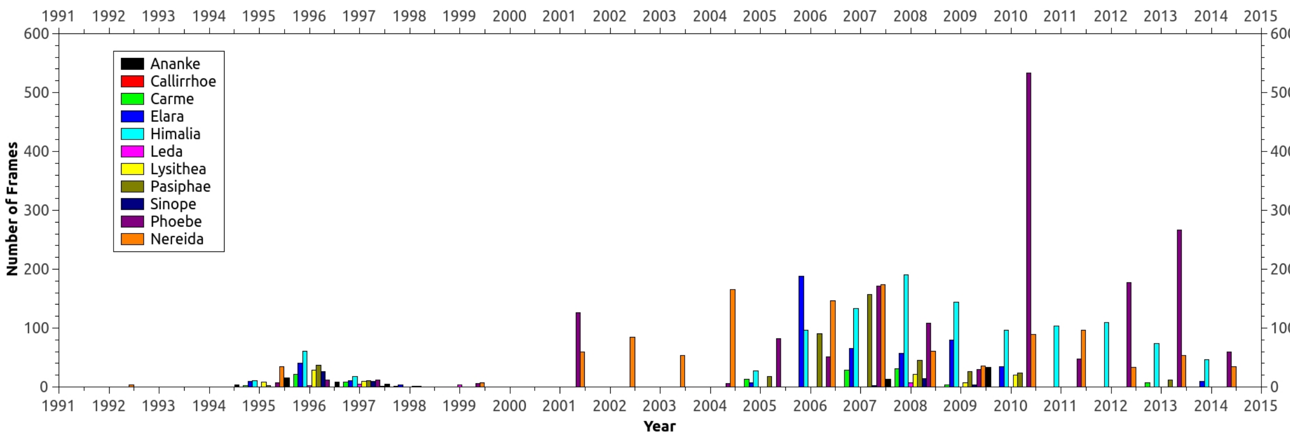

Fig. 1. Distribution of observations of the satellites over time at OPD.

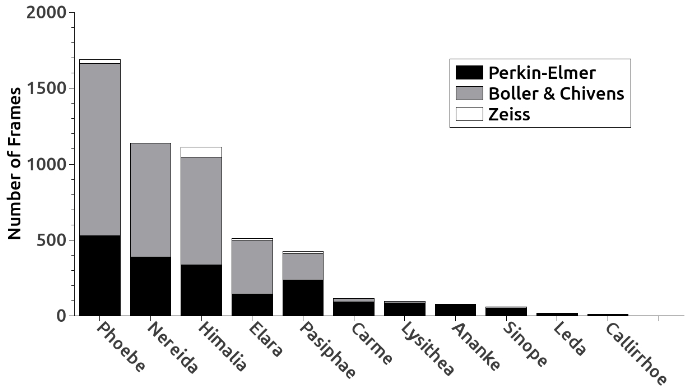

Fig. 2. Number of frames observed by satellite by OPD telescope.

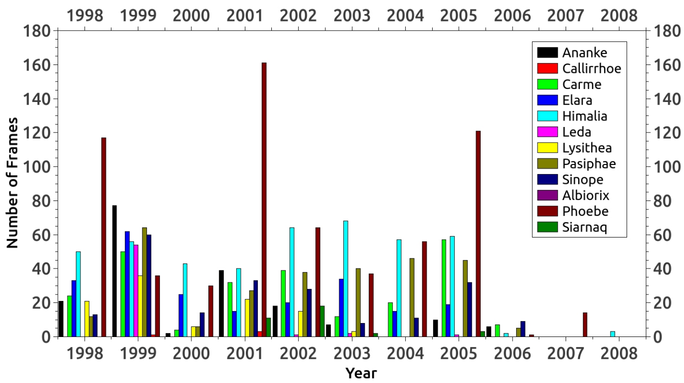

Fig. 3. Distribution of the observations of the satellites over time from observations at OHP.

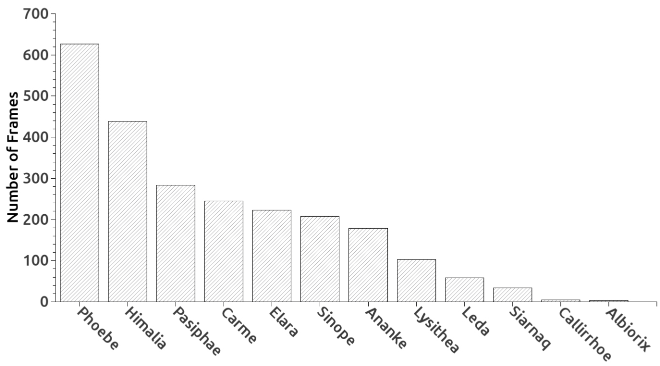

Fig. 4. Number of frames by satellite observed at OHP.

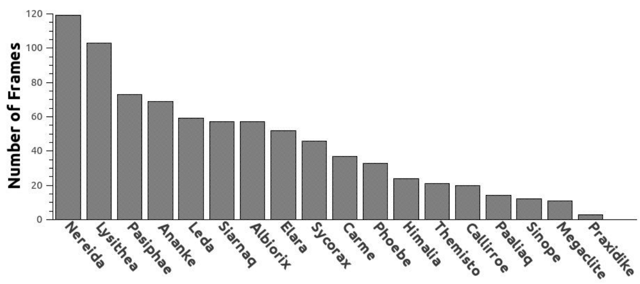

Fig. 5. Number of frames by satellite observed at ESO.

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 these observations, 2408 were 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) sizes, 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 in paralel with, and using the same observational and astrometric procedures of the program that observed stars along the sky path of trans-neptunian objects (TNOs) to identify candidates to stellar occultation (see Assafin et al. (2010, 2012); Camargo et al. (2014)). A total of 810 observations for irregular satellites were obtained. Fig 5 shows the number of frames

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 possible.

The astrometric reductions were made with 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 may jeopardize the center determination. PRAIA automatically recognizes catalog stars and determines (α, δ) with a user-defined model 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 each frame, we used the six constants polynomial model to relate the (x, y) measurements with the (X, Y) tangent plane coordinates. For ESO, we also used a 3rd degree polynomial model 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. More recent versions of the ephemeris are available, but it was necessary keep these ephemeris to finish the work.

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. When the time was not 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 (see Assafin et al. (2012) for more detail informations).

For each night a sigma-clipping procedure was performed to eliminate discrepant positions (outliers). A threshold of 120 mas and a deviation of more than 2.5 sigmas from the nightly average ephemeris offsets were adopted.

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

[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	Offsets (sigma) σ_α mas	σ_δ mas	Nr frames (nights)	UCAC4 stars	Mag
Himalia	290	45	238 (18)	37	14
Elara	230	118	99 (12)	32	16
Lysithea	107	79	53 (8)	41	18
Leda	207	79	6 (2)	46	19
Pasiphae	157	92	144 (13)	22	17
Callirrhoe	66	35	9 (1)	3	21
Carme	97	94	68 (7)	49	18
Sinope	155	77	37 (8)	42	18
Ananke	93	185	52 (7)	40	19
Phoebe	73	95	410 (22)	6	16
Nereid	200	142	289 (29)	8	19

The offsets (sigma) are the average standard deviations in the ephemeris offsets from the (α, δ) reductions with the UCAC4 catalog.

From Table 3 to 7 we list the average dispersion (standard deviation) of the position offsets with regard to the ephemeris α and δ obtained by telescope for each satellite. The final number of frames, number of nights in parenthesis, the mean number of UCAC4 stars used in the reduction and the mean magnitude V are also given. The dashed lines separate the satellites from different families with similar orbital parameters: Himalia Group (Himalia, Elara, Lysithea and Leda), Pasiphae Group (Pasiphae, Callirrhoe and Megaclite), Ananke Group (Ananke and Praxidike), Carme and Sinope that are the only sample of their groups. From Saturn, Siarnaq and Paaliaq are from the Inuit Group while Phoebe and Albiorix are the only sample of their groups.

The difference of the dispersion of offsets in different telescopes for the same satellite is caused by the distribution of the observations in the orbit. This distribution can be seen in Fig 6 for Carme, 7 for Pasiphae and for all objects in online material. Since the observations cover different regions of the orbit, the dispersion of the offsets may vary for different telescopes for a single satellite. For Nereid, due to its high eccentric orbit, the observations are located between 90° and 270° of True Anomaly where Nereid remains most of the time.

No solar phase correction was applied to the positions. For the biggest satellite of Jupiter, Himalia, it was identified that the maximum deviation in the position due to phase angle is 1.94 *mas* using the phase correction described in

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

Boller & Chivens					
Satellite	Offsets (sigma) σ_α mas	σ_δ mas	Nr frames (nights)	UCAC4 stars	Mag
Himalia	83	43	560 (31)	57	14
Elara	55	43	294 (23)	53	16
Lysithea	23	42	7 (2)	60	18
Pasiphae	128	71	140 (14)	57	17
Carme	68	111	22 (4)	45	18
Sinope	59	17	4 (1)	22	18
Phoebe	43	48	810 (42)	17	16
Nereid	61	45	514 (38)	20	19

Same as in Table 3.

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

Zeiss					
Satellite	Offsets (sigma) σ_α mas	σ_δ mas	Nr frames (nights)	UCAC4 stars	Mag
Himalia	112	72	56 (4)	91	14
Elara	17	21	10 (1)	146	16
Pasiphae	24	25	11 (1)	140	17
Phoebe	37	30	19 (1)	16	16

Same as in Table 3.

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

OHP					
Satellite	Offsets (sigma) σ_α mas	σ_δ mas	Nr frames (nights)	UCAC4 stars	Mag
Himalia	49	66	357 (43)	49	14
Elara	52	61	187 (25)	37	16
Lysithea	63	50	84 (13)	56	18
Leda	118	33	48 (7)	14	19
Pasiphae	101	75	248 (32)	39	17
Carme	114	96	204 (29)	39	18
Sinope	196	73	169 (25)	43	18
Ananke	100	89	141 (20)	62	19
Phoebe	30	31	516 (63)	51	16
Siarnaq	46	98	20 (6)	32	20

Same as in Table 3.

Lindegren (1977). For the other satellites, which are smaller objects, this deviation is even smaller. Since the error of our measurements is one order higher, this effect was not considered.

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

ESO					
Satellite	Offsets (sigma) σ_α mas	σ_δ mas	Nr frames (nights)	UCAC4 stars	Mag
Himalia	76	74	23 (2)	1153	14
Elara	112	87	46 (4)	1492	16
Lysithea	76	88	90 (6)	695	18
Leda	60	125	44 (3)	632	19
Pasiphae	70	114	66 (5)	836	17
Callirrhoe	29	33	16 (1)	493	21
Megaclite	52	34	10 (1)	445	22
Ananke	225	19	57 (3)	761	18
Praxidike	7	38	2 (1)	1934	21
Carme	140	110	37 (4)	1074	18
Sinope	339	70	11 (2)	1542	18
Themisto	894	28	16 (2)	1232	21
Phoebe	102	57	32 (5)	312	16
Siarnaq	86	66	56 (6)	283	20
Paaliaq	301	59	11 (4)	382	21
Albiorix	76	50	46 (6)	330	20
Sycorax	150	82	35 (9)	375	21
Nereid	115	78	99 (12)	362	19

Same as in Table 3.

Table 9. 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	-	16	25	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.

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 are in the ICRS. The catalog also contains epoch of observations, the position error, filter used, estimated magnitude (from PSF fitting) and telescope origin. The magnitude errors can be as high as 1 mag; they are not photometrically calibrated and should be used with care. The position errors were estimated from the dispersion of the ephemeris offsets of the night of observation of each position. Thus, these position errors are probably overestimated, as there must be ephemeris errors present in the dispersion of the offsets. These positions are freely available in electronic form at the CDS as in Table 8.

The number of positions acquired is significant compared to the number used in the numerical integration of JPL ephemeris (Jacobson et al. 2012) as shown in Table 9.

Table 8. CDS data table sample.

Himalia							
RA (ICRS) h m s	Dec ° ′ ″	RA error (mas)	Dec error (mas)	Epoch (jd)	Mag	Filter	Telescope
16 59 11.6508	-22 00 44.855	17	12	2454147.78241319	16.0	C	BC
16 59 11.6845	-22 00 44.932	17	12	2454147.78332384	15.8	C	BC
16 59 11.7181	-22 00 44.978	17	12	2454147.78422477	16.0	C	BC
16 59 11.7818	-22 00 45.143	17	12	2454147.78602662	15.9	C	BC
16 59 11.8188	-22 00 45.232	17	12	2454147.78693750	16.0	C	BC
17 17 11.0344	-22 47 19.415	30	24	2454205.63885463	16.1	U	BC
17 17 11.0270	-22 47 19.381	30	24	2454205.63959167	16.1	U	BC
17 17 11.0258	-22 47 19.366	30	24	2454205.64031875	16.1	U	BC
17 17 11.0192	-22 47 19.417	30	24	2454205.64104583	16.1	U	BC

This sample corresponds to 9 observations of Himalia from February 16, 2007 and April 15, 2007. Tables contain the ICRS coordinates of the irregular satellites, the position error estimated from the dispersion of the ephemeris offsets of the night of observation, the estimated magnitude, the filter used and telescope origin. The filters may be U, B, V, R or I following the Johnson system; C stands for clear (no filter used), resulting in a broader R band magnitude. E, OH, PE, BC and Z stand respectively for the ESO, OHP, Perkin-Elmer, Bollen & Chivens and Zeiss telescopes.

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 with regard to the ephemeris mentioned in Sect. 3. Taking Carme as example, we plot in Fig. 6 the mean ephemeris offsets for each night and their dispersions (1 sigma error bars) as a function of the true anomaly in right ascension (6a) and declination (6b). Fig. 6b 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 from observations by 4 telescopes using different cameras and filters are in good agreement, meaning that there is an error in the ephemeris of Carme, most probably due to an error in its orbital inclination.

This pattern in declination was also seen for other satellites like Pasiphae (Fig: 7) and Ananke (plots for other satellites with significant number of observations can be seen in Appendix A of online material). For some satellites, the orbital coverage is not enough to clearly indicate the presence of systematic errors in specific orbital elements. However, comparing the internal mean errors of the reductions (Table 2) with the external position errors estimated from the dispersion of the ephemeris offsets (Tables 3 to 7), we see position error values much larger than expected from the mean errors. This means that besides some expected astrometric errors, significant ephemeris errors must also be present.

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 suitable astrometric 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 9). Systematic errors in the ephemeris were found for at least some satellites (Ananke, Carme, Elara and Pasiphae).

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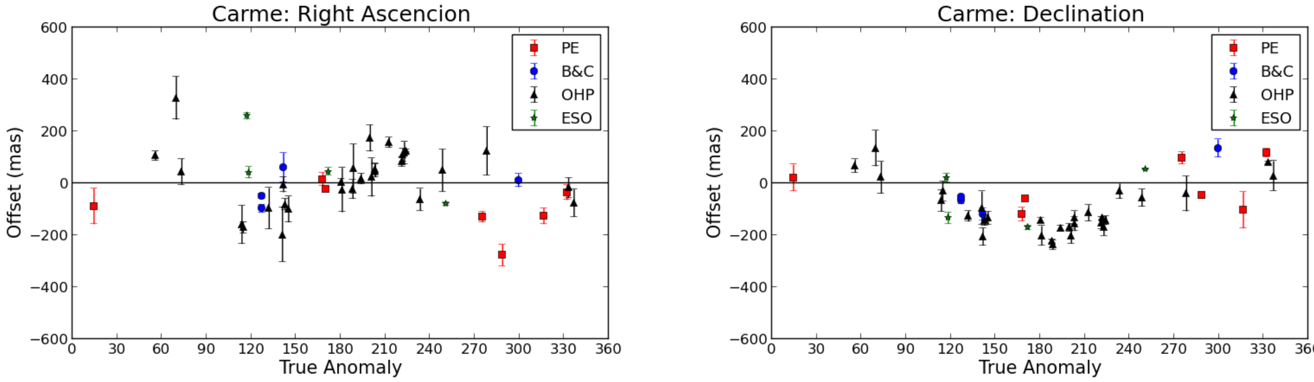
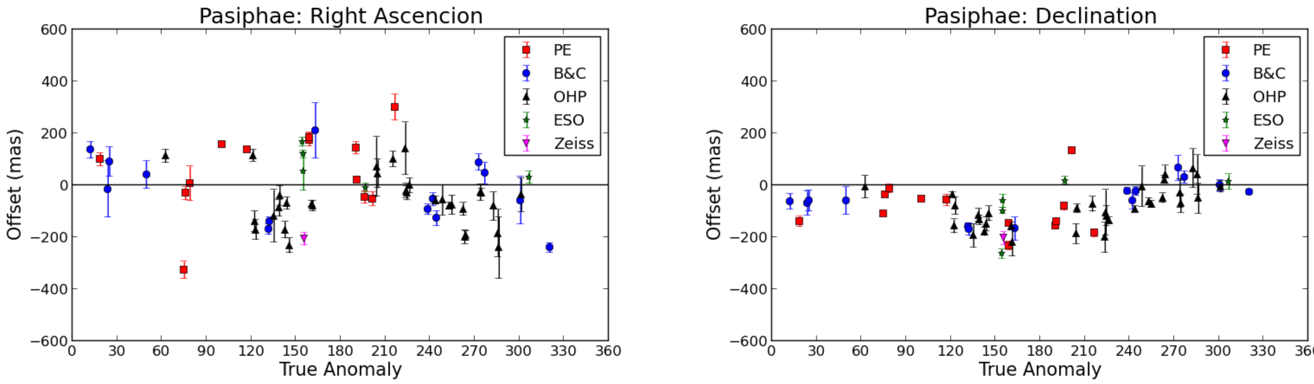


(a) Right Ascension
(b) Declination

Fig. 6. Mean ephemeris offset and dispersion (1 sigma error bars) in the coordinates of Carme taken night by night by true anomaly.



(a) Right Ascension
(b) Declination

Fig. 7. Mean ephemeris offset and dispersion (1 sigma error bars) in the coordinates of Pasiphae taken night by night by true anomaly.

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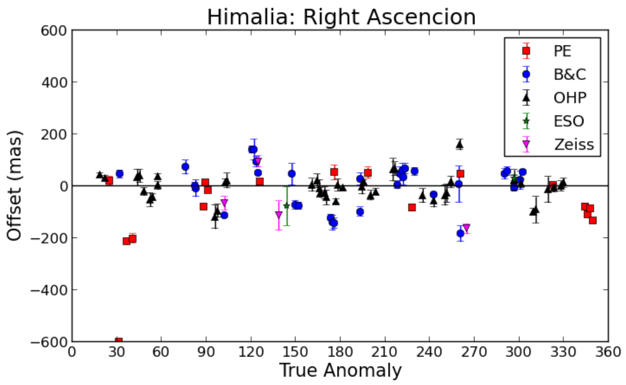
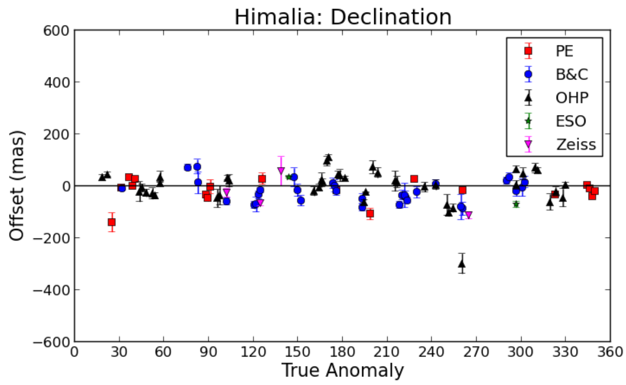
Appendix A: Offsets x True Anomaly images

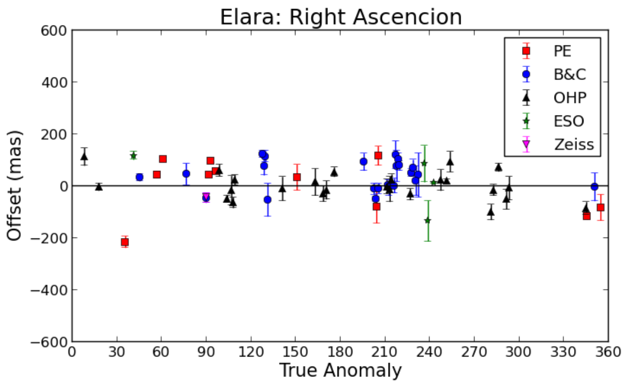


(a) Right Ascension

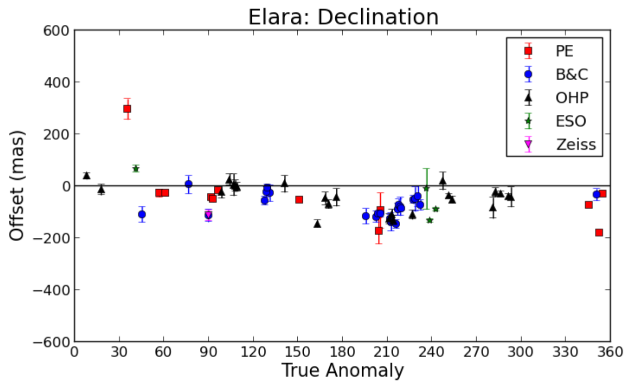


(b) Declination

Fig. A.1. Mean ephemeris offset and dispersion (1 sigma error bars) in the coordinates of Himalia taken night by night by true anomaly.

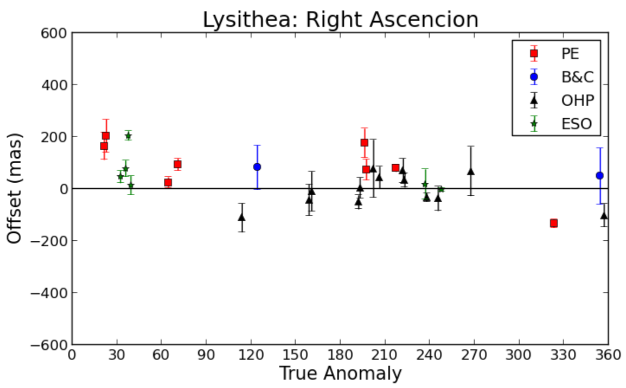


(a) Right Ascension

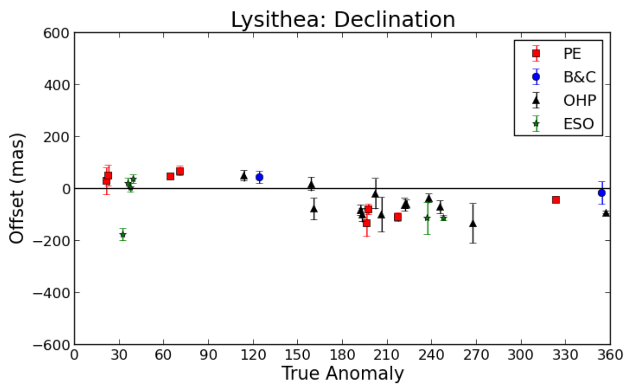


(b) Declination

Fig. A.2. Mean ephemeris offset and dispersion (1 sigma error bars) in the coordinates of Elara taken night by night by true anomaly.

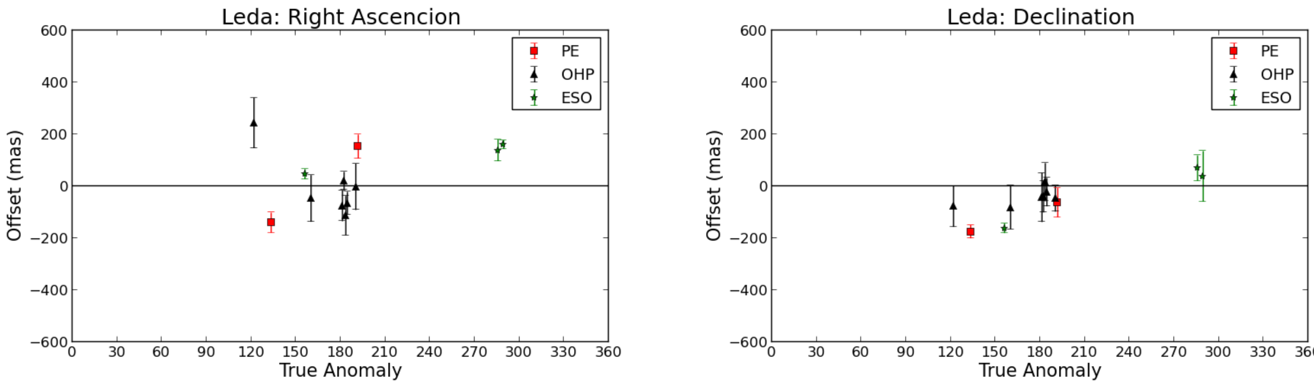


(a) Right Ascension



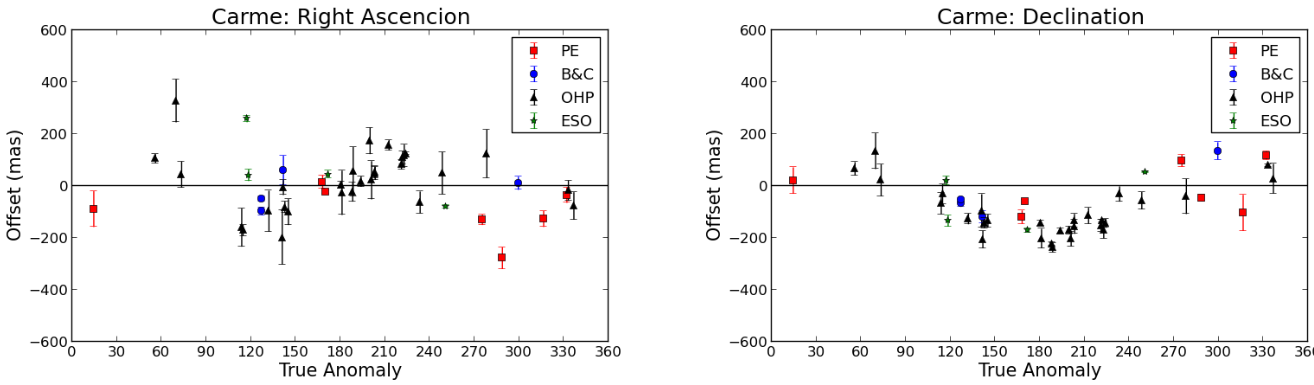
(b) Declination

Fig. A.3. Mean ephemeris offset and dispersion (1 sigma error bars) in the coordinates of Lysithea taken night by night by true anomaly.



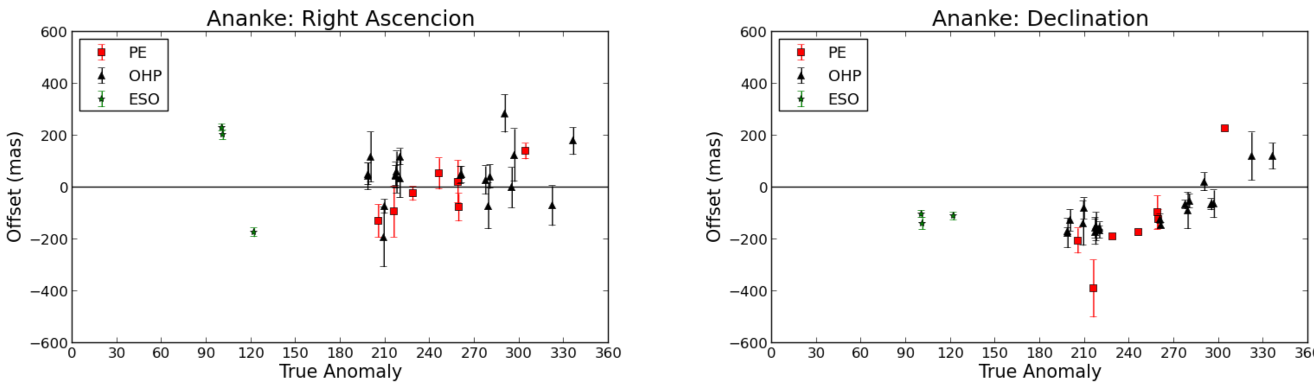
(a) Right Ascension (b) Declination

Fig. A.4. Mean ephemeris offset and dispersion (1 sigma error bars) in the coordinates of Leda taken night by night by true anomaly.



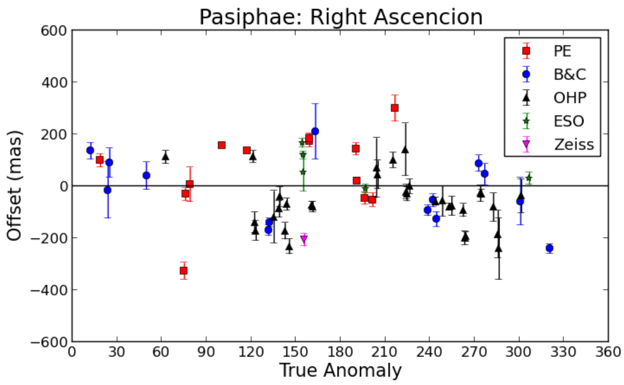
(a) Right Ascension (b) Declination

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

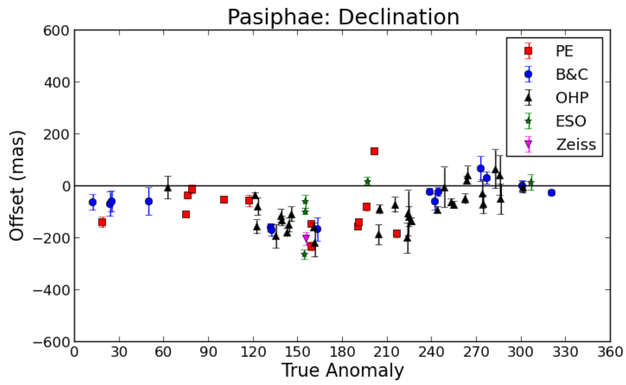


(a) Right Ascension (b) Declination

Fig. A.6. Mean ephemeris offset and dispersion (1 sigma error bars) in the coordinates of Ananke taken night by night by true anomaly.

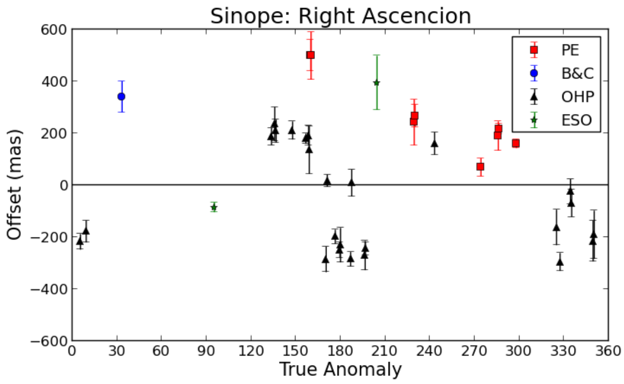


(a) Right Ascension

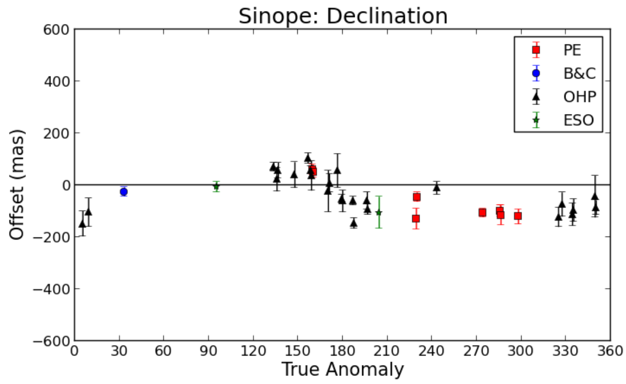


(b) Declination

Fig. A.7. Mean ephemeris offset and dispersion (1 sigma error bars) in the coordinates of Pasiphae taken night by night by true anomaly.

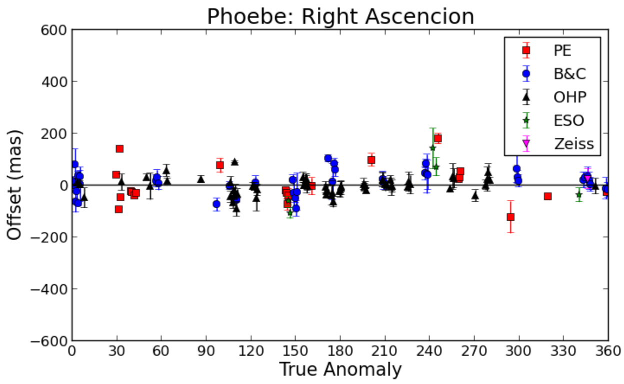


(a) Right Ascension

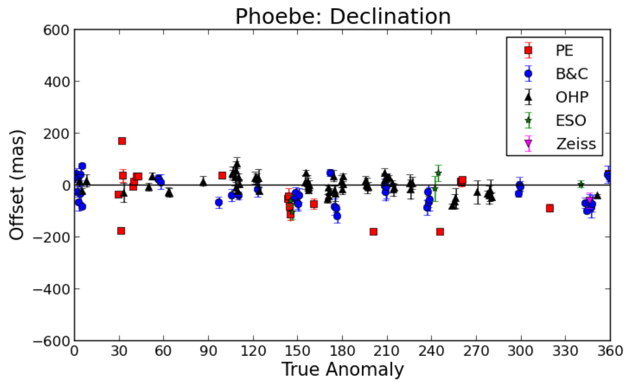


(b) Declination

Fig. A.8. Mean ephemeris offset and dispersion (1 sigma error bars) in the coordinates of Sinope taken night by night by true anomaly.

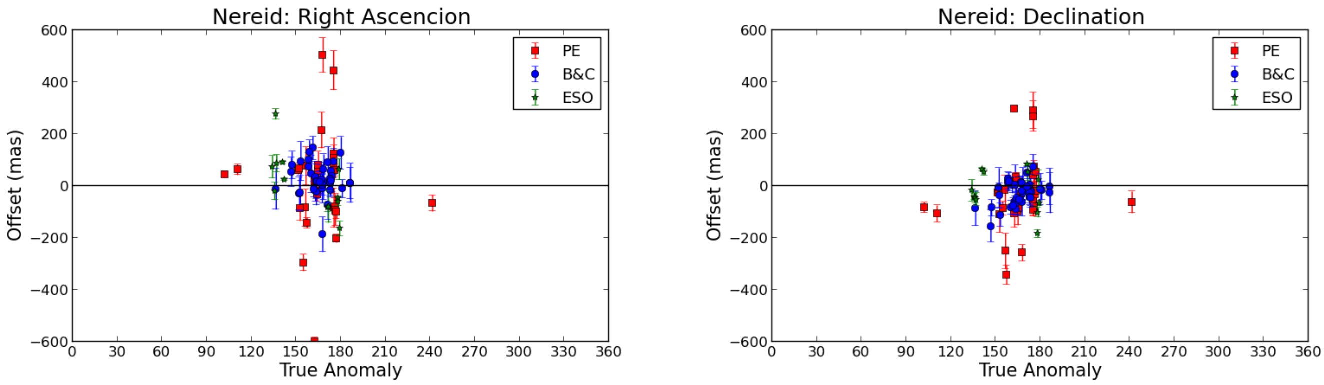


(a) Right Ascension



(b) Declination

Fig. A.9. Mean ephemeris offset and dispersion (1 sigma error bars) in the coordinates of Phoebe taken night by night by true anomaly.



(a) Right Ascension

(b) Declination

Fig. A.10. Mean ephemeris offset and dispersion (1 sigma error bars) in the coordinates of Nereid taken night by night by true anomaly.