Astrometry of the Neptune-Triton System

Altair Ramos Gomes Júnior

August 12, 2016

Introduction

In this report I present the preliminary results of the astrometric reductions of the images from the Observatório do Pico dos Dias (OPD) in Brazil. The aim is to obtain precise positions for the Neptune - Triton system and to investigate the orbit of Neptune alone around the Sun. The telescopes used were the Perkin-Elmer (160) with a diameter of 1.6m, the Boller & Chivens (IAG) with a diameter of 0.6m, and the Zeiss telescope with a diameter of 0.6m.

The observations were carried out since 1992 when a CCD big enough was installed in the OPD. The planet and satellite have been constantly observed, and still are, by our group. There were many CCDs (IKON, IXON, CCD101, CCD106, ...) and many filters (V, R, I, No Filter, ...) utilized.

There was a total of 9942 images from June 1992 to September 2015. Many of the oldest images had no coordinates in header or they were wrong. Sometimes the filter was missing. Many nights had two exposure sets. The first one with low exposure times so Neptune was not saturated, but there were few reference stars in the field. The second one with higher exposure time so Triton was brighter and had more reference stars than with the the previous exposure, but the image of Neptune were saturated.

In Table 1 it is summarized the final number of images for Neptune (short-exposure observations) and Triton (all observations) for the 3 telescopes. It is also shown the number of positions where Neptune and Triton were identified automatically in the same image (short-exposure observations for precision premium; see Section Tests).

Table 1: Number of positions by object by telescope

Telescope	Neptune	Triton	Matches
160	610	1154	547
IAG	2381	2659	1888
Zeiss	258	345	222
Total	3249	4158	2657

Number of positions identified of Neptune and Triton by telescope. Matches: Number of positions where Neptune and Triton were identified automatically in the same image.

Fig. 1 shows the distribution of positions where Neptune and Triton are identified in the same image (short-exposure observations) over the years. Figs 2-4 summarizes the distribution of positions with Neptune and Triton in the same image by filter obtained in the Perkin-Elmer , the Boller & Chivens and the Zeiss telescopes, respectively.

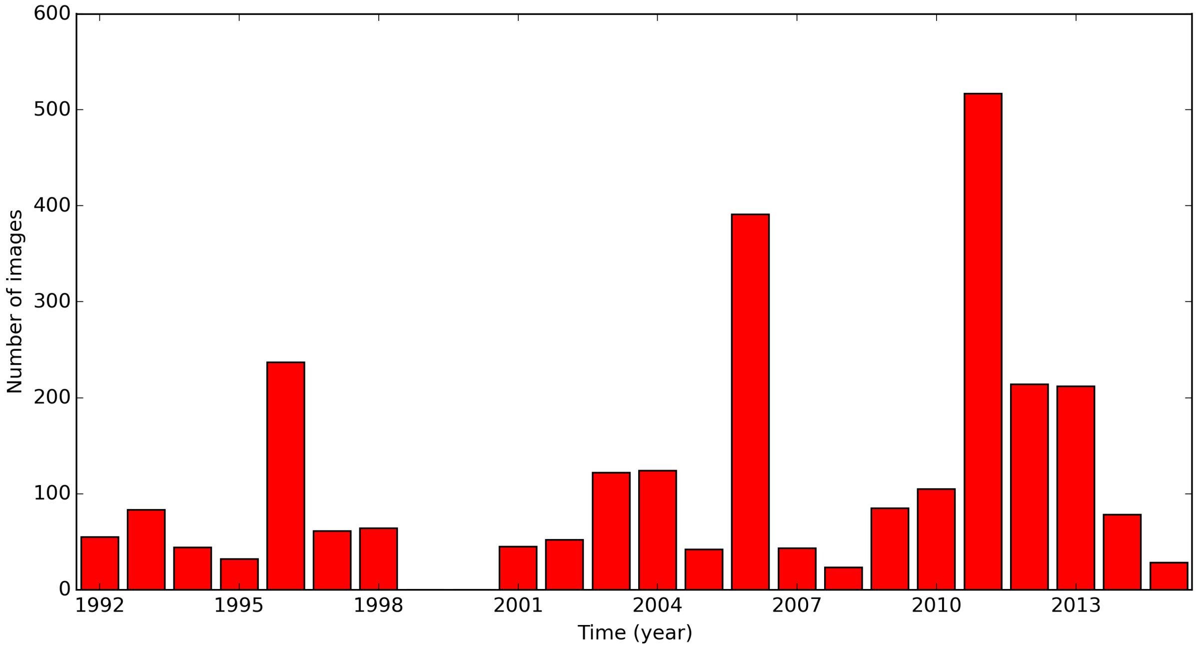

Figure 1: Distribution of positions with Neptune and Triton in the same image (short-exposure observations) by year.

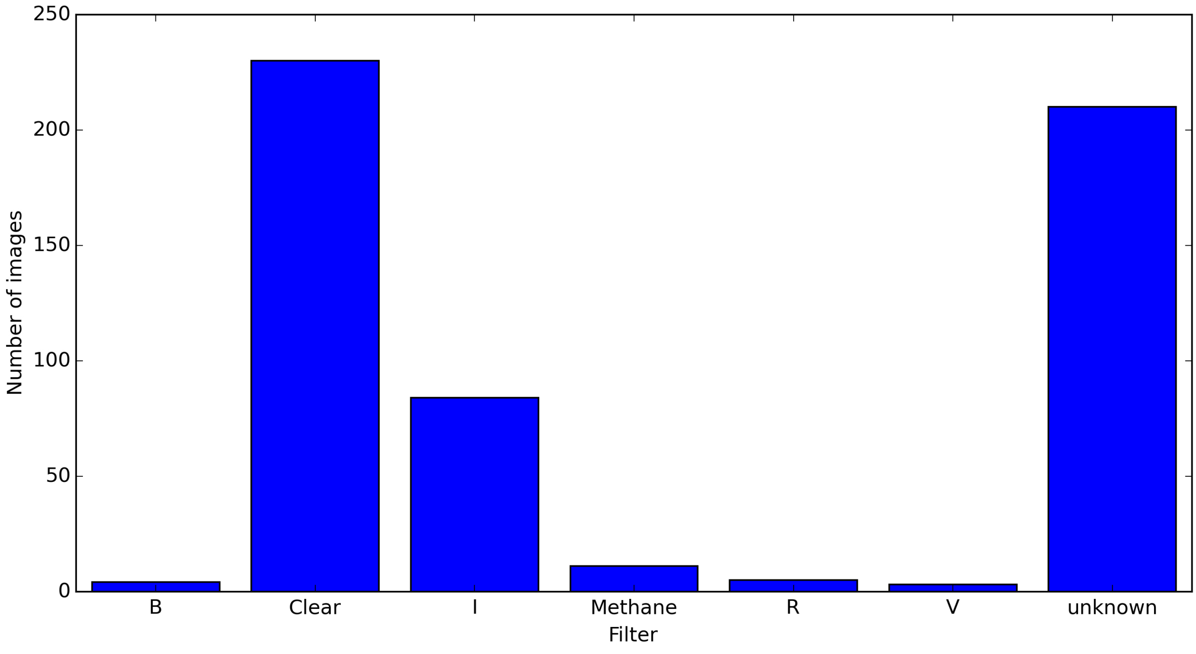

Figure 2: Distribution of positions with Neptune and Triton in the same image (short-exposure observations) by filter for the Perkin-Elmer telescope.

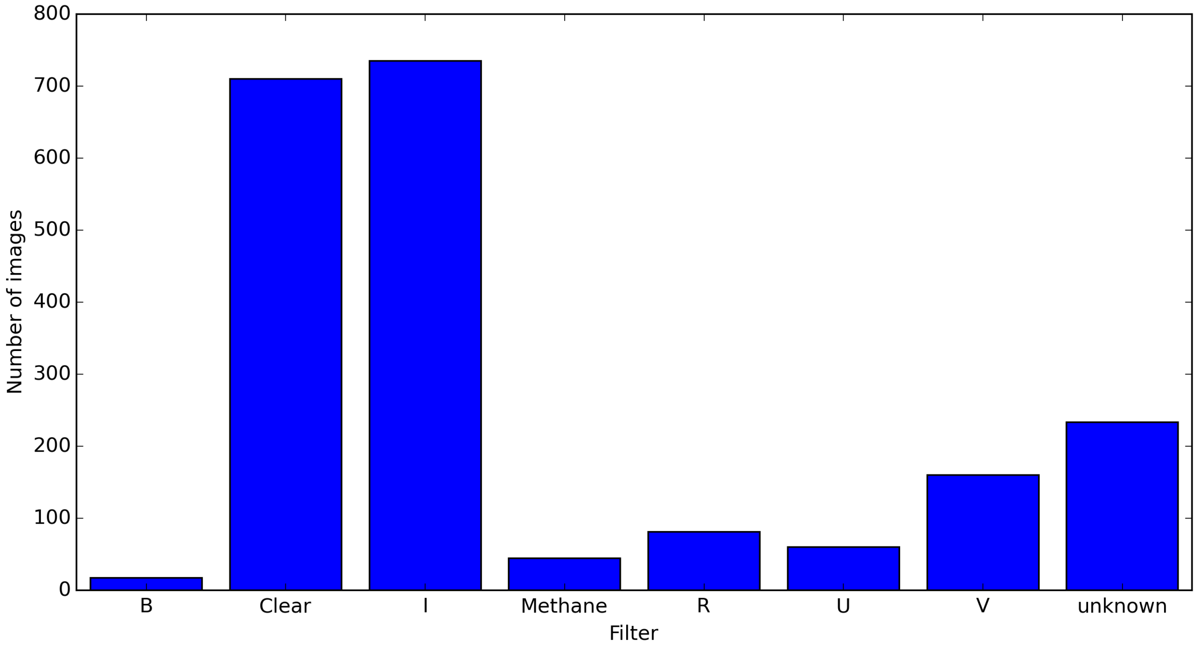

Figure 3: Same as in Fig 2 for the Boller & Chivens telescope.

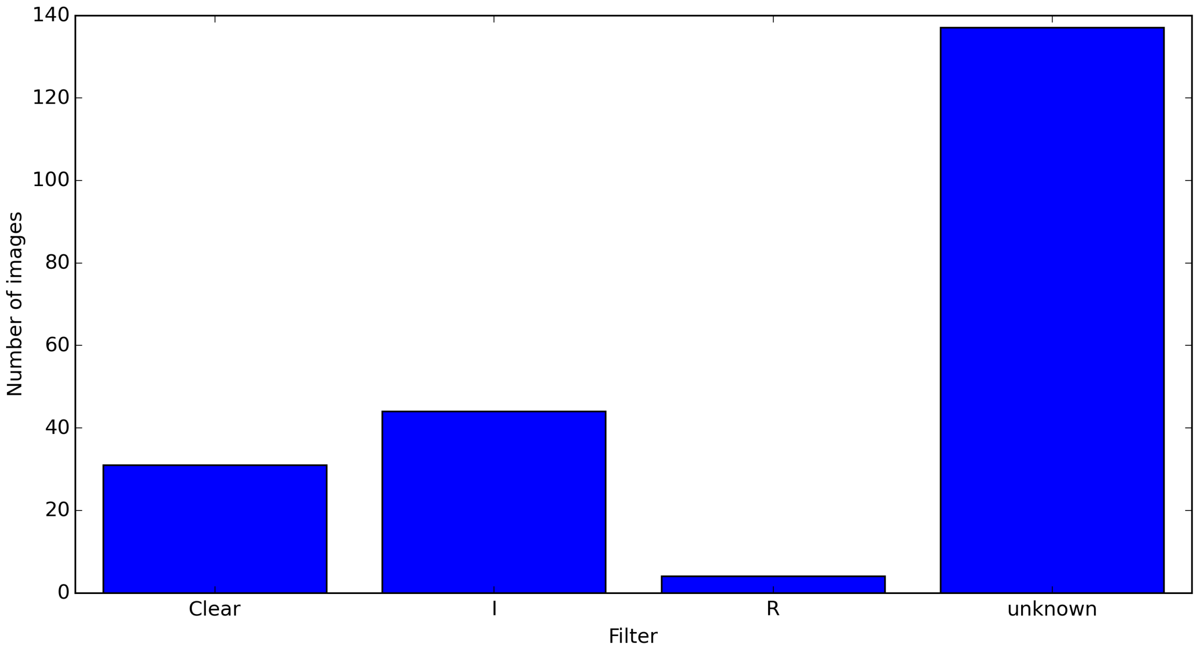

Figure 4: Same as in Fig 2 for the Zeiss telescope.

It is possible to see that the

Reduction

The images were reduced using PRAIA, developed by Marcelo Assafin. To avoid the missing or wrong coordinates I used the coordinates of the ephemeris as input. This way PRAIA could identify reference stars in the images. The reference catalogue used was UCAC4. The ephemeris used to identify Neptune and Triton in the images was DE430+NEP081. The positions where the image of Neptune were saturated was removed of the results.

In Table 2 it is presented the mean errors in X and Y of the bidimensional Gaussian used to fit the PSF of the objects using only short-exposure observations.

Table 2: Table of erros of the reduction. Gaussian error stands for the error in X and Y of the bidimensional Gaussian used to fit the PSF. Mean offset errors is the average dispersion of the positions of each night using only short-exposure observations.

Telescope/Satellite	Gaussian error		Mean offet errors	
	X (mas)	Y (mas)	RA (mas)	DEC (mas)
160/Neptune	8	8	42	37
160/Triton	14	14	28	29
IAG/Neptune	9	9	36	38
IAG/Triton	20	20	34	37
Zeiss/Neptune	9	9	28	32
Zeiss/Triton	27	27	28	35

We applied the digital coronagraphy technique to test if the scattered light of Neptune would influence in the Triton's photocenter. No influence was identified in the 1 mas range.

From the offsets in the sense "position minus ephemeris" identified I made statistics night by night to eliminate discrepant positions with a sigma-clip procedure where offsets (modulus) larger than 80 mas or 2-sigma discrepant from the mean offset were removed. This procedure was applied for each set of observations (short exposures and long exposures) separately.

Chromatic Refraction Test

Table 3 shows the colors for Triton (Pascu et al., 2006) and Neptune Schmude et al. (2016). Their colors are very different in the blue region. So it is expected that their positions have influence of chromatic refraction with different intensities. The apparent position of Neptune, which is more blue than Triton, would be more shifted towards the zenith than the Triton's position. There may also be noted that in 1992 Neptune had just exited the galactic plane, so the reference stars were redder due to dust.

Object	U-B	B-V	V-R	R-I	V-I
Triton (leading side)		+0.696±0.009			+0.766±0.006
Triton (trailing side)		+0.699±0.006			+0.776±0.007
Neptune	+0.14	+0.39	-0.29	-1.05	+0.76*

Table 3: Colors of Triton and Neptune. Leading side is the hemisphere of Triton that is in the direction of its movement. Trailing side is the opposite hemisphere. *calculated from V-R and R-I colors.

To test the effects of chromatic refraction I used the method of Benedetti-Rossi et al. (2014) on all nights with observations distributed over more than 1.5h of hour angle.

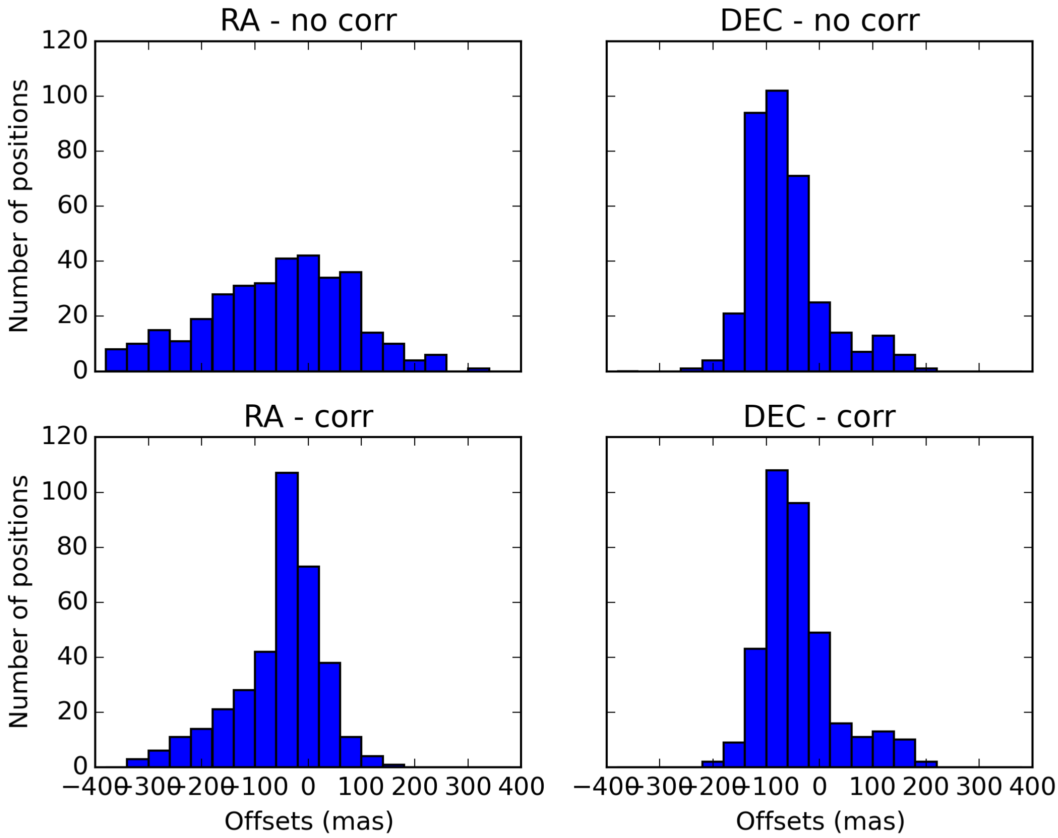

Figure 5: Distribution of the offsets of Neptune for the nights August 22, 2004 and September 25, 2011.

Date	Filter	ΔH	B	Nimg	Nstars	RA no corr	DEC no corr	RA corr	DEC corr
1992-06-09	Clear	1.57	+0.295	13	11	190± 54	25± 76	-43± 15	65± 68
1992-07-19	Clear	1.63	+0.203	17	24	50± 46	117± 37	1± 26	125± 36
1993-06-24	Clear	1.61	-0.073	10	17	-17± 26	-38± 48	-21± 22	-40± 48
1993-06-25	Clear	2.63	+0.034	12	8	-37± 26	70± 75	-40± 24	72± 74
1993-08-20	Clear	3.35	+0.204	31	29	15± 76	-83± 43	-7± 34	-75± 44
1993-08-22	Clear	2.87	+0.177	35	9	-47± 63	-74± 44	-15± 38	-67± 46
1996-06-22	Clear	1.68	+0.244	19	16	-25± 51	-32± 35	-48± 18	-20± 35
1996-10-02	Clear	1.97	+0.312	16	6	252±192	-60± 73	-59±126	10± 79
1997-06-01	Clear	4.89	+0.348	91	11	-155±189	-112± 36	-120±107	-81± 40
1997-06-02	Clear	5.24	+0.219	60	10	-113±125	-84± 36	-73± 48	-61± 33
1998-06-06	Clear	2.51	+0.384	35	11	-140±101	-66± 42	-13± 56	-33± 41
1998-09-03	Clear	1.52	+0.302	20	10	-86± 63	-75± 49	20± 26	-51± 47

Table 4: Obtained parameters and offsets from adjustments of 160 images.

Teoretically, the difference in the positions of the objects in the sense Triton - Neptune compared to the difference in the ephemeris over a night would cause the following effects.

- RA: the difference in the offsets would be positives in the East side of the sky, negative in the West side and zero in the culmination, with the assumption that only chromatic refraction affects the offsets.
- DEC: the difference in the offsets in the culmination would be positive (Neptune is in the North side in both nights for the site). Farther from the culmination the difference in the offsets would be more positive.

Fig **??** clearly shows that that the chromatic refraction is affecting the offsets confirming our expectation. It is possible to see that the distribution of the offsets for the 5 night are very similar over the hour angles observed.

We use the equation

$$\Delta[\alpha, \delta] = V_{\alpha,\delta}(\phi, \delta, H) \cdot \Delta B, \tag{1}$$

to model the chromatic refraction of the nights. $\Delta[\alpha, \delta]$ is the position offset for each coordinate (α, δ), $V_{\alpha,\delta}(\phi, \delta, H)$ is the first part of refraction which is due to the position of the observed objects and is a function of the latitude of the site (ϕ), of the object's declination (δ), and of the hour angle (H) and ΔB is the the second part is the differential chromatic refraction which is due to the atmospheric conditions and the wavelength (λ) of the object and of the stars in the field. This equation is available in Benedetti-Rossi et al. (2014) where it was applied for observations of Pluto.

The offsets corrected by chromatic refraction of the 5 nights is presented in Fig. 6.

In Table 5 it is shown the mean of the difference in the offsets of Triton and Neptune for each night and their dispersions. We made two tests in the chromatic refraction, the first one we made the correction in the difference of the offsets of both objects. In the second test we made the corrections in the offsets separately for each object, then we took the difference between them.

Table 5: Mean and Standard deviation of the difference in the offsets of Triton - Neptune before and after the chromatic refraction correction

Night	No correction		Correction 1		Correction 2	
	RA	DEC	RA	DEC	RA	DEC
PE:1997-05-31	83+-138	-1+-34	58+-88	-22+-34	58+- 88	-22+-34
PE:1997-06-01	120+-118	31+-26	84+-38	9+-27	84+-38	9+-27
BC:2003-07-27	-13+-111	25+-70	32+-70	7+-70	35+-100	6+-70
BC:2004-08-22	-11+-43	53+-38	22+-22	41+-37	19+- 23	42+-37
BC:2011-09-25	-33+-34	70+-17	5+-23	55+-16	5+- 23	55+-16

"Correction 1" means that the correction was made in the difference of the offsets of Triton and Neptune. "Correction 2" means that the correction of chromatic refraction was made in the offsets of Triton and Neptune separately then we took the difference between them.

It is possible to see that the dispersion of the offsets in RA after the correction is much smaller than before the correction. The mean offsets in RA also show significant difference. For DEC the dispersion does not change, but the mean offsets presents significant difference. It is also possible to see that the results for both tests are basically the same, with the exception of the night of 2003 in RA.

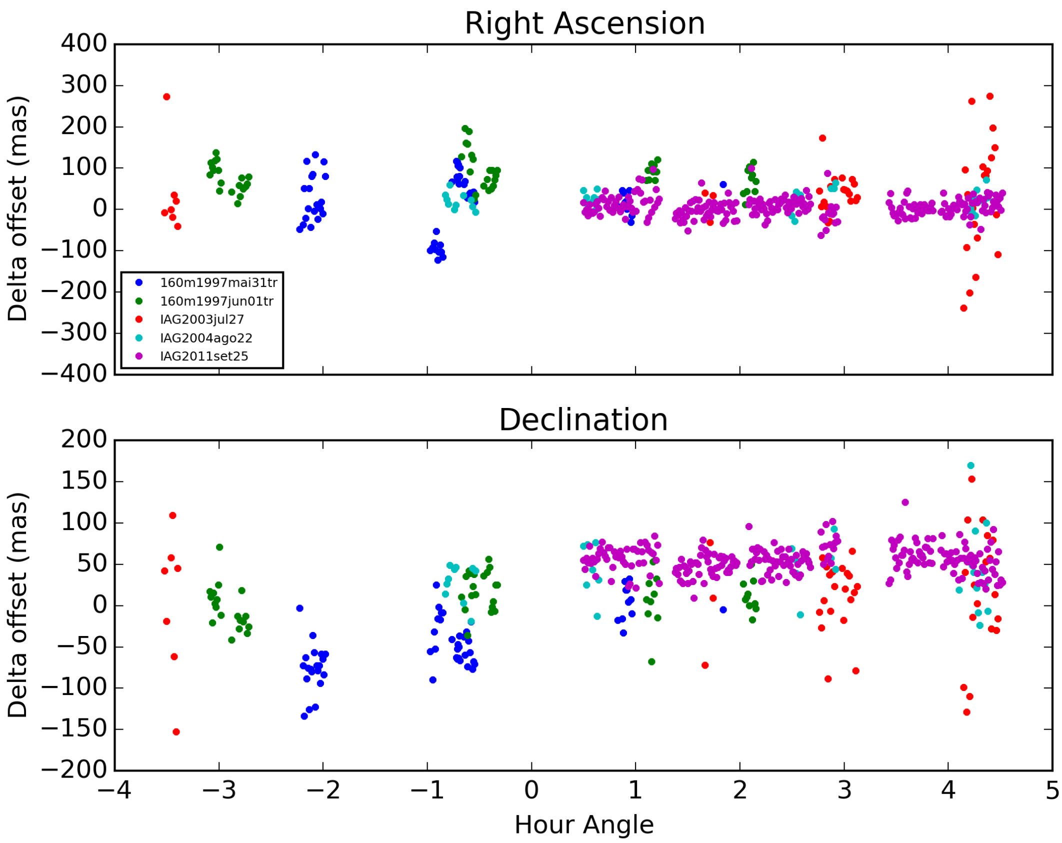

Figure 6: Same as in Fig. **??** but corrected by chromatic refraction.

In Table 6 it is shown the values of ΔB obtained in the fit of the offsets of Triton and Neptune separately and their differences. The minimum and maximum values of Hour Angle for each night is also presented.

Final Remarks

Fig 7 shows the offsets of Neptune, respectively, in RA e DEC for all the positions not eliminated in the sigma-clip procedure. Fig 8 shows the mean offsets of each night and respective discrepancy (error bars).

Fig 9 shows the difference between the relative observed positions and the relative ephemeris positions of Triton and Neptune in the sense Triton - Neptune where they were identified in the same frame and not eliminated by the sigma-clip procedure.

Fig 10 shows the difference in the mean offsets night by night for all matched nights and not eliminated by the sigma-clip procedure in the sense Triton - Neptune. The dispersions (error bars) is the mean value of the dispersion in the night for each satellite.

It seems that there are long term systematic errors in the orbit of Neptune, and in the orbit of Triton around Neptune, but it is too soon to state that with confidence. We must still further refine the positions. We plan to do the following:

- Separate images by filter.
- It may be required the use of a specific PSF for Neptune due to its large size.

Table 6: Results of the fit of ΔB in the 5 nights for the difference Triton - Neptune and for each object separately.

Night	Filter	H_{min}	H_{max}	ΔH	Object	ΔB	err ΔB
PE:1997-05-31	Clear	-3.0	2.1	5.1	T-N	0.214	0.004
					Neptune	-0.219	0.004
					Triton	-0.006	0.004
PE:1997-06-01	Clear	-2.6	2.2	4.8	T-N	0.239	0.004
					Neptune	-0.347	0.004
					Triton	-0.107	0.004
BC:2003-07-27	Clear	-3.5	4.8	8.3	T-N	0.052	0.003
					Neptune	-0.015	0.002
					Triton	0.038	0.003
BC:2004-08-22	Clear?	-0.8	4.3	5.1	T-N	0.048	0.004
					Neptune	-0.059	0.003
					Triton	-0.015	0.004
BC:2011-09-25	I	0.4	4.5	4.1	T-N	0.046	0.002
					Neptune	-0.046	0.002
					Triton	0.000	0.002

- Further refinements in the data may be needed as we further investigate these position sets.

Bibliography

Benedetti-Rossi, G., Vieira Martins, R., Camargo, J. I. B., Assafin, M., and Braga-Ribas, F. (2014). Pluto: improved astrometry from 19 years of observations. *Astronomy & Astrophysics*, 570:A86.

Pascu, D., Storrs, A. D., Wells, E. N., Hershey, J. L., Rohde, J. R., Seidelmann, P. K., and Currie, D. G. (2006). Hst bvi photometry of triton and proteus. *Icarus*, 185(2):487–491.

Schmude, Jr., R. W., Baker, R. E., Fox, J., Krobusek, B. A., Pavlov, H., and Mallama, A. (2016). The Secular and Rotational Brightness Variations of Neptune. *ArXiv e-prints*.

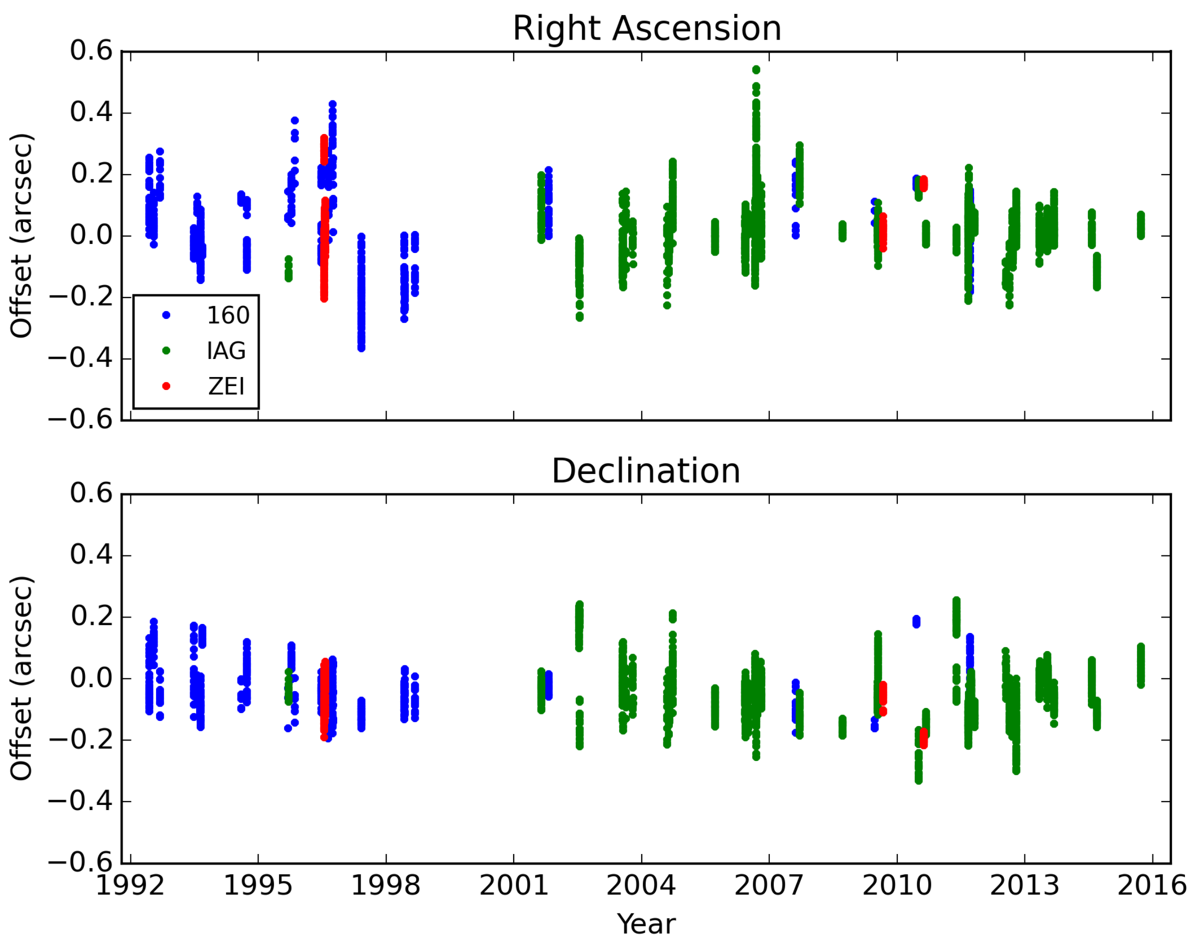

Figure 7: Neptune - All Offsets

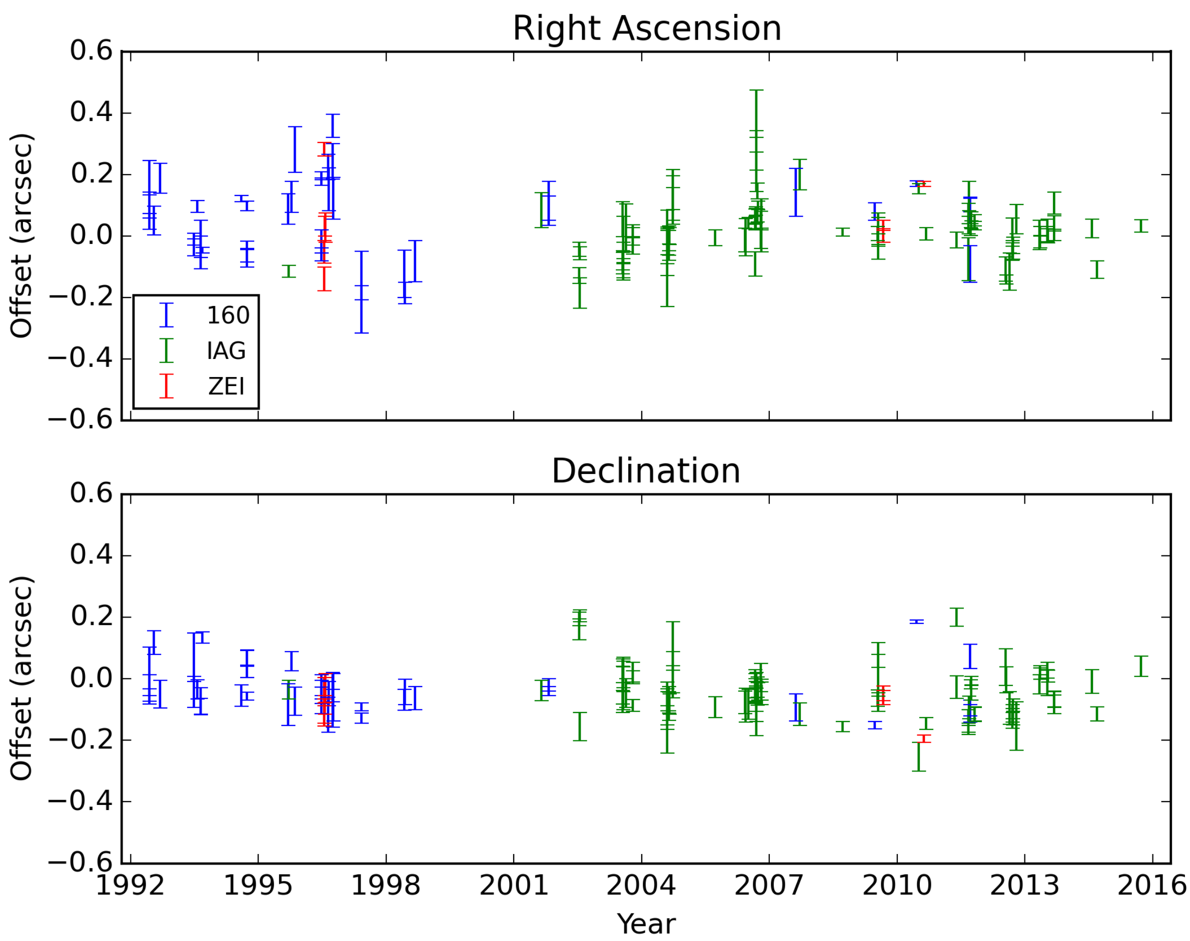

Figure 8: Neptune - Mean offsets by day

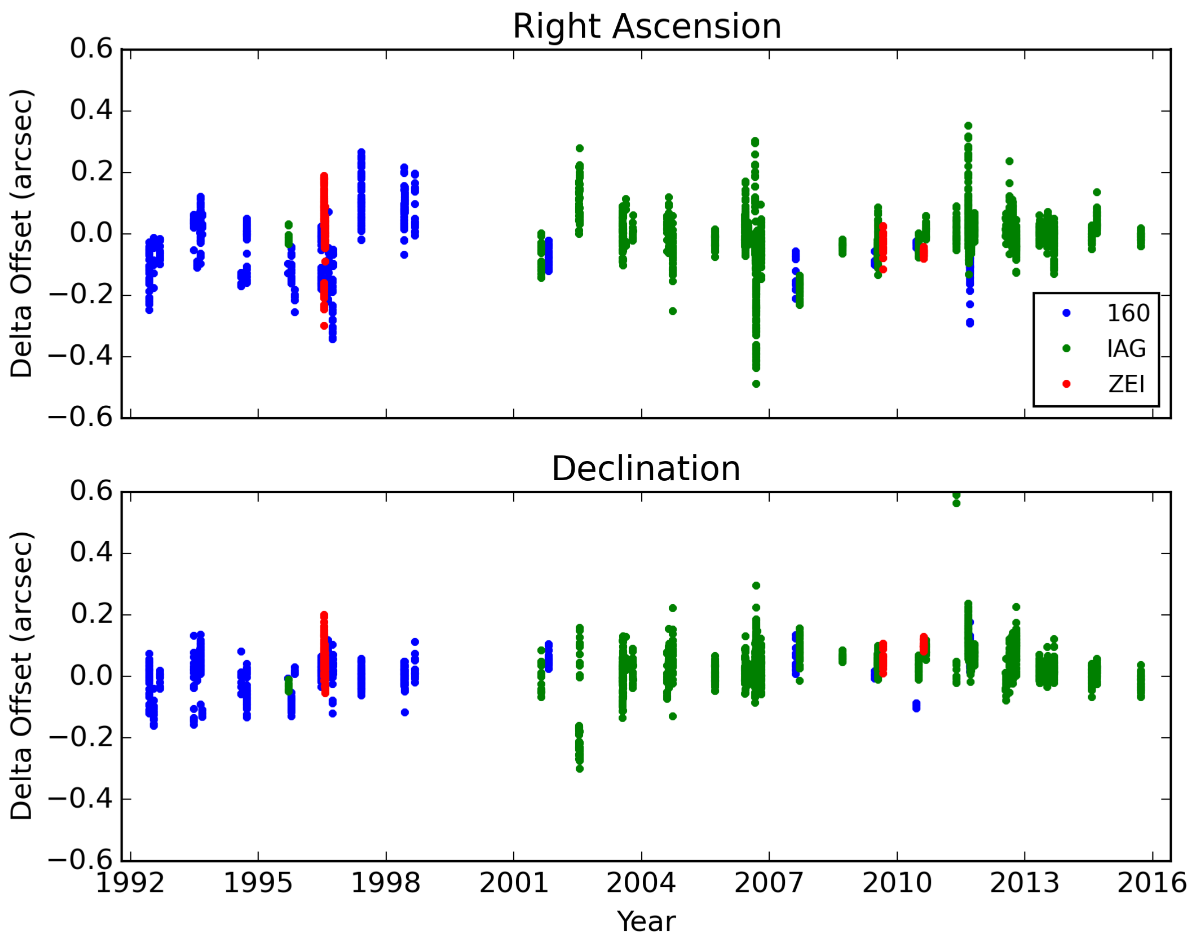

Figure 9: Difference between the offsets of Triton and Neptune - All data

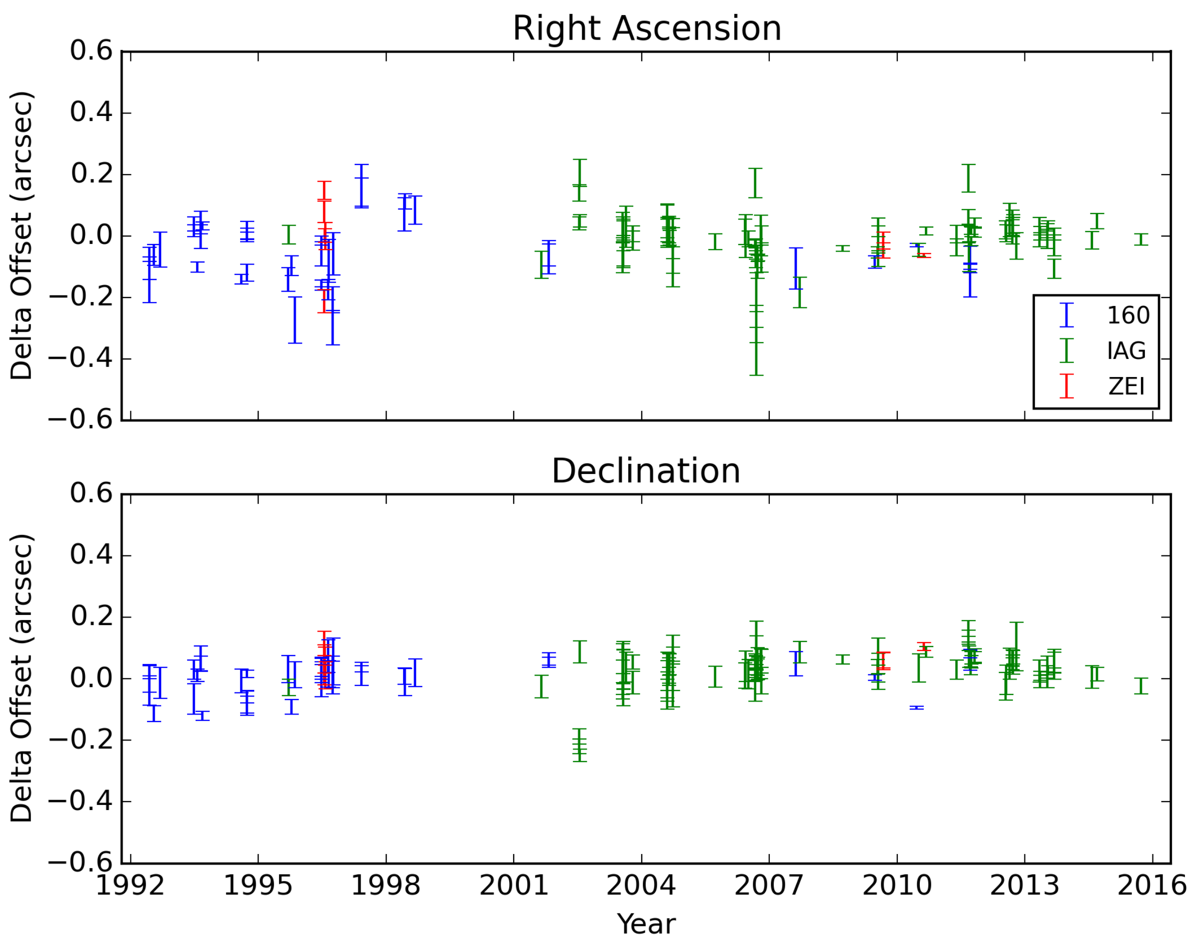

Figure 10: Difference between the offsets of Triton and Neptune - Mean offset by day