ASTRONOMY & ASTROPHYSICS
SUPPLEMENT SERIES

MAY I **1999**, PAGE 445

Astron. Astrophys. Suppl. Ser. **136**, 445–451 (1999)

CCD observations of Nereid and a new orbital determination⋆,⋆⋆

C.H. Veiga[1], **R. Vieira Martins**[1], **and Cl. Le Guyader**[2]

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

[2] Institut de Mécanique Céleste et de Calcul des Éphémérides, 77 avenue Denfert-Rochereau F-75014 Paris, France
e-mail: Claude.Leguyader@bdl.fr

Received September 14, 1998; accepted January 8, 1999

Abstract. 229 CCD positions of Nereid taken between 1993 and 1998 are presented. Many of the observations were taken near the periapsis. Considering also the other published positions we have a good distribution of the observations on the eccentric orbit of the satellite. Using a numeric integration method we fitted all these observations in order to determine one state vector for the orbit. The observed minus calculated standard deviation for all observations is $0\farcs23$, and for our observations it is $0\farcs16$.

Key words: astrometry — planets and satellites: Nereid

1. Introduction

Nereid is the most eccentric satellite of the known Solar System ($e = 0.75$). This satellite of Neptune was discovered by Kuiper (1949) and from 1949 until now, there are 79 ground based published observations of this satellite. Its magnitude is about 19.5 and therefore there are not many Nereid's astrometric positions and those are not uniformly distributed in time. From 1949 to 1969 there were 47 photographic observations made by Van Biesbroeck and Roemer (Rose 1974 and Van Biesbroeck et al. 1976). The majority of this observations (35) are distributed uniformly between 1949-1955 and the remaining (12) in the interval 1967-1969. In 1977-78 two positions were taken at MacDonald Observatory by Shelus & Mulholland (Veillet 1982). From 1981 to 1987 there are 15 positions observed by Veillet (1988), 3 by Landgraf (1988) and 8 by the authors (Veiga et al. 1996). All these positions were obtained with photographic plates. In 1987, four CCD positions were obtained by Shaefer & Shaefer (1988). During the Voyager 2 encounter with Neptune 83 unpublished positions of Nereid where determined (Jacobson et al. 1991). In this paper we present 229 new CCD astrometric positions of this satellite obtained in 23 nights in the period 1993-1998.

Many computations of Nereid's orbit have been taken. The orbital parameters were calculated by Rose (1974) using a Keplerian orbit. In 1975, Mignard (1975) studied the orbital motion of a satellite with large eccentricity considering the perturbation of the Sun and applied these results to Nereid. Later, Mignard (1981) applied his theory to Van Biesbroeck observations and gave the expressions to calculate the mean elliptical elements for any given time. In Veillet (1982) and Veillet & Bois (1988) new determination was made of the initial elliptic elements for the Mignard's theory and Vieira Martins (1989) added the perturbations of Triton to the Mignard expressions. Jacobson (1990) used all the published observations to calculate the barycentric state vector of Nereid referred to the earth mean equator and equinox of 1950.0 at Julian ephemeris date 2447080.5. Finally, Jacobson et al. (1991) made a new determination of the state vector using additionally the 2 ground observations of Pascu and 83 positions given by the Voyager spacecraft. In this paper we made a new determination of the state vector for Nereid considering the previous ground base observations put together with our positions.

The large eccentricity and the small number of observations of Nereid make the determination of the periapsis very difficult. This could be a domineering source of errors in its orbit determination. To study this problem we placed many of our CCD observations near the periapsis. In particular, some 199 observations of Nereid was taken at this region. Using these positions and all others published, we fitted a new orbit for Nereid through a numerical integration.

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

⋆⋆ Tables 1 and 2 are 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/Abstract.html

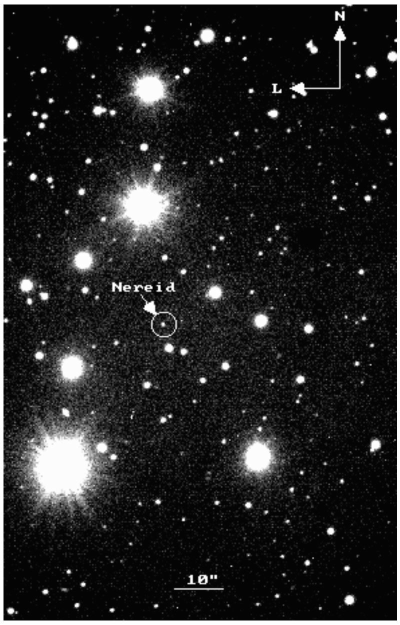

Fig. 1. a) CCD frame observed at 08/22/1996, $3^{h}12^{m}48^{s}$ TU. Exposure time $2^{m}30^{s}$. CCD dimension 770 × 1152 pixels

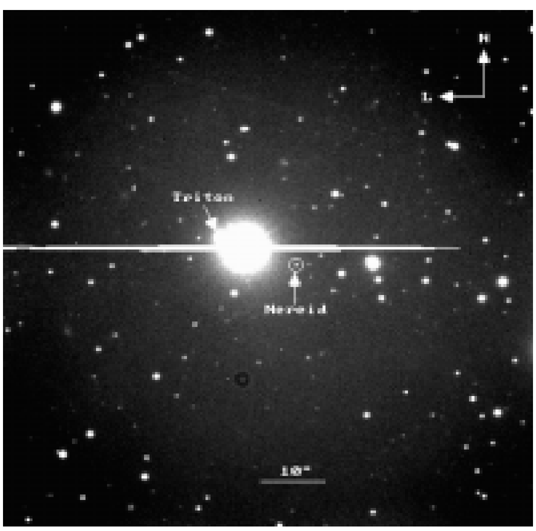

Fig. 1. b) CCD frame observed at 06/06/1998, $4^{h}9^{m}31^{s}$ TU. Exposure time 4^{m}. CCD dimension 1024 × 1024 pixels

2. The observations, reduction and astrometric calibration

All 229 observations were made at the Cassegrain-focus of the Laboratório Nacional de Astrofísica (LNA) 1.6 m reflector (latitude $= -23°$) and they are distributed through 23 nights between 1993 and 1998. The focal distance of the used configuration is 15.8 m which gives a scale of $13''$/mm at the focal plane. The LNA latitude is well suited to observe Neptune since its present declination range is around $-21°$. Therefore, we have for every night several positions of Nereid near the zenith.

Table 3. The state vector at Julian ephemeris date 2433007.5 (1949 April 1 at 0^{h} TU) referred to the barycenter of the Neptunian system and to the mean equator and equinox J2000.0. The positions are given in astronomical units and the velocities in astronomical units per day

Position (UA)	Velocity (UA/day)
3.05667133049352911E-2	1.58295918371424726E-4
1.76800233558712140E-2	5.48150536863375440E-4
1.08925085961084200E-2	2.93164262521805727E-4

Three CCDs were used in our observations. An EEV-05.20.0.202 which is an array with 770 × 1152 square pixels, each measuring 22.5 μm which corresponds to $0\farcs293$, and two SI003AB CCDs with 1024 × 1024 square of side with 24 μm ($0\farcs312$). No filter was used and the exposure time was about 5 minutes. In Fig. 1 two of our frames of Nereid are seen.

The CCD frames with Nereid present some peculiar features. All images of Neptune and Triton are saturated. In particular, the image of Neptune saturates also some CCD columns (see Fig. 1b) and so its image is not measurable. On the other hand, Triton has their image strongly contaminated by the light scattered by Neptune. We have also that the brightest stars, which are suitable for the merging of the local catalog in a reference catalog, are also saturated. For Nereid, its images are very faint and sometimes just over the sky noise. Finally, the large variation of the distance between Neptune and Nereid gives many different positions of Nereid in the frames, which contributes to the non-uniformity of the reductions.

Therefore the reduction and the astrometric calibration of Nereid images are very difficult and the accuracy achieved is not always satisfactory. These problems will be considered in Sect. 4.

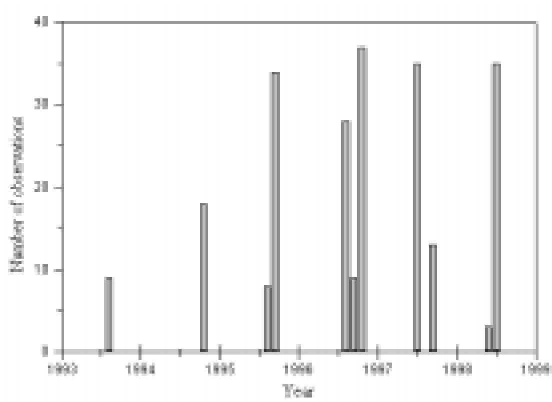

Fig. 2. Histogram of the CCD observations of Nereid with respect to time. Each bar corresponds to an observational mission

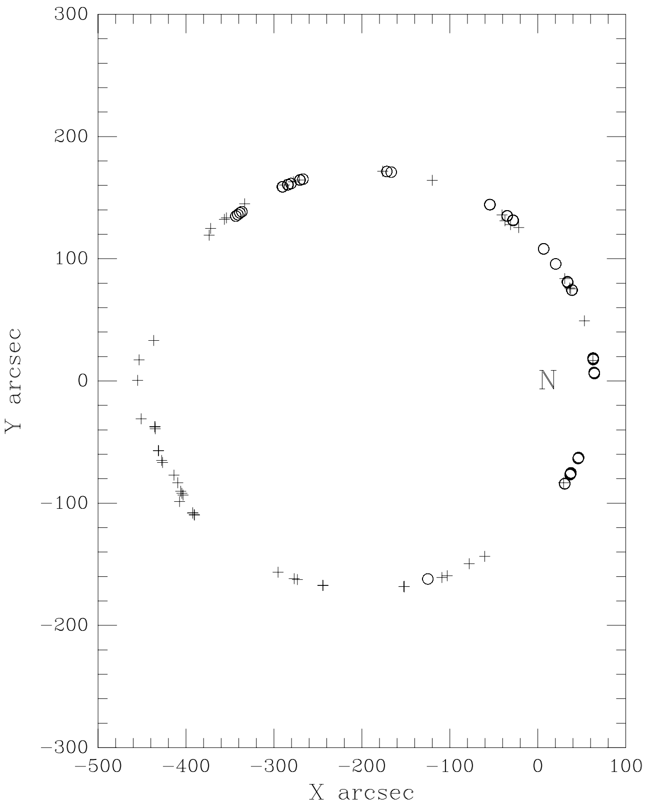

Fig. 3. Fitted positions of Nereid from 1949 to 1998 on the elliptic orbit. The present CCD observations are represented by circles

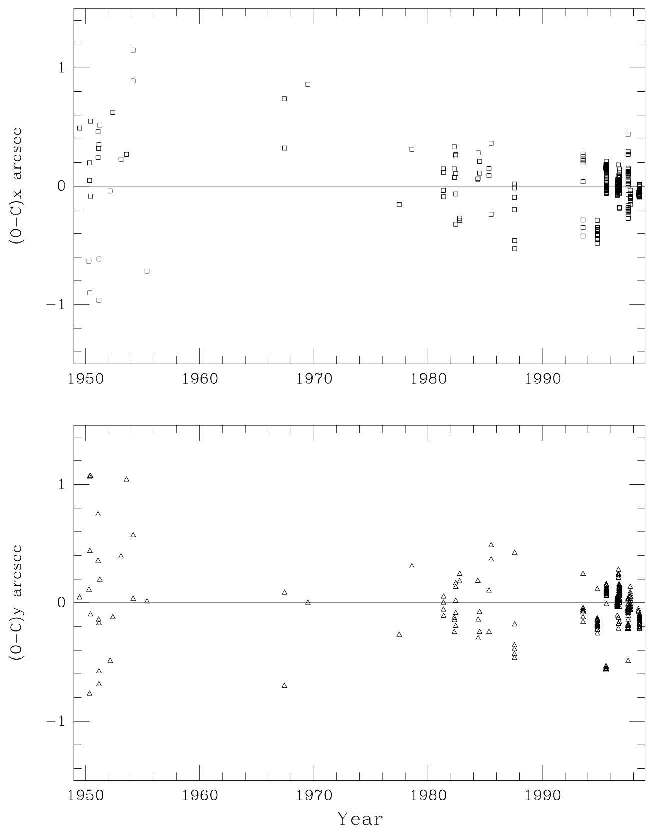

Fig. 4. Observed minus calculated residuals as function of time for Nereid fitted observations

The ASTROL routines package (Colas & Serrau 1993) was employed to find the center of the satellite and stellar images. Each center was determined by a two-dimensional Gaussian fitting a small circular area around the image and where the background was removed by a second degree polynomial.

The errors upon the centering procedure were at $0\farcs03$ for Nereid and at $0\farcs01$ for the field stars. The errors upon the centering of Triton are very difficult to estimate since the images are always saturated.

The astrometric calibration was performed using the method presented and tested for this satellite in Vieira Martins et al. (1996) (see also Assafin et al. 1997a, 1997b and 1997c). It consists on the setting of an astrometric catalogue for the stars on the CCD, using their images in the Digitized Sky Survey and the positions of nearby stars from the Guide Star Catalogue corrected by the PPM Catalog.

The RMS of the residuals in the secondary catalog stars were about $0\farcs12$ for a mean of 20 stars by frame. However for some few frames the number of such stars is lesser than 5.

Depending on the elongation of Nereid, there are three types of frames:

- type 1: the images of Nereid and Triton are in the same frame and there are many reference stars around the two satellites;
- type 2: the images of the two satellites are in the same frame but the reference stars are only on one side of each satellite;
- type 3: The image of Triton is not in the frame and Nereid is near to the center and surrounded by reference stars.

We will see in Sect. 4 that these types of frames are important in the study of the accuracy of our results.

The images of Triton is always saturated and immersed into the light diffused by Neptune. However, when Triton and Nereid are in the same frame, we measured the center of Triton except for five images of 1993 where Triton entered into the saturated region, produced by the CCD charge bleeding due to the strong light of Neptune.

Therefore, we considered two set of positions. In the first one, we computed the right ascension and the declination of the satellite for all 229 observations. In the second set we take the positions of Nereid related to Triton for the 174 frames were the two satellites appear together and the Triton's image is measurable. The theoretical positions of Neptune were calculated using DE403 (Standish et al. 1995).

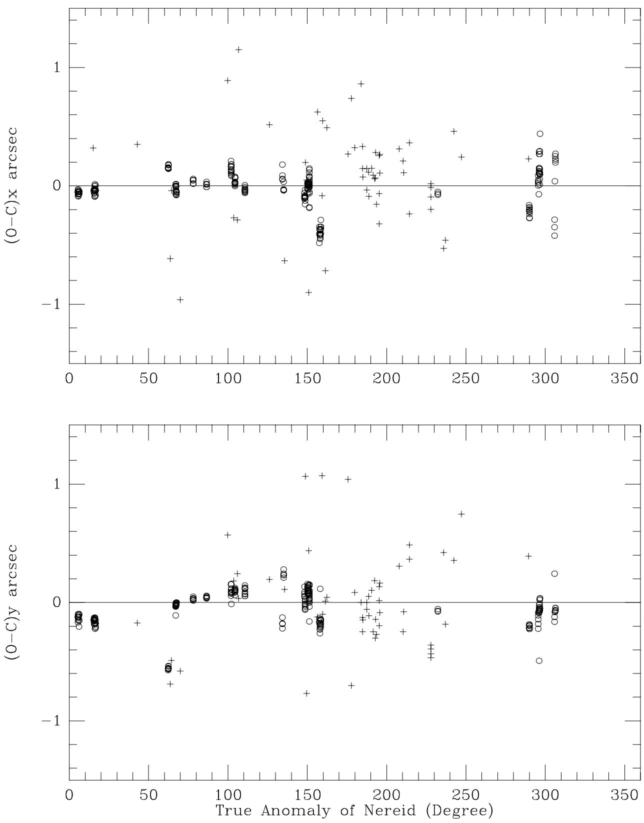

Fig. 5. The same as Fig. 4 but referred to the true anomaly. The circles correspond the our CCD observations

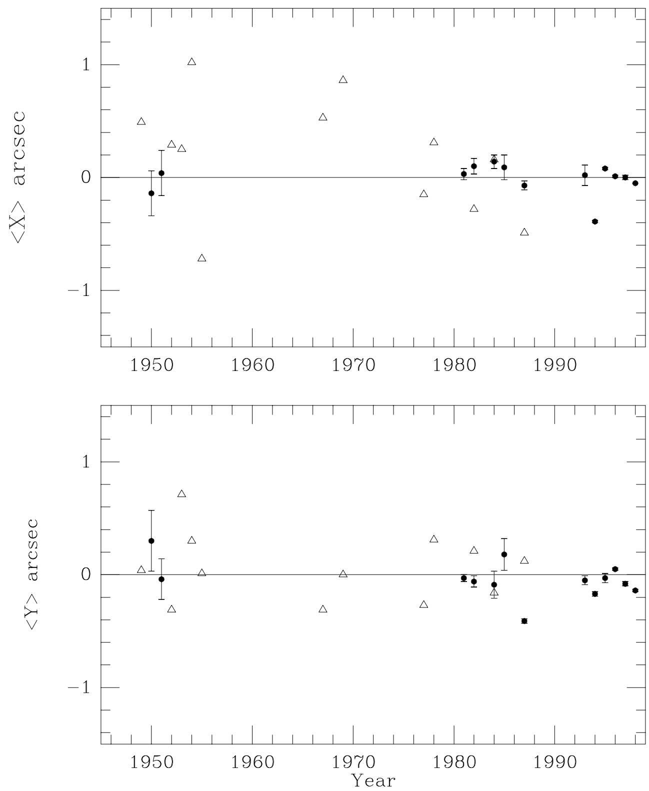

Fig. 6. The means and their errors for the fitted observations grouped by observer and opposition. The cases corresponding to one or two observations are represented by triangles. For many points the bars corresponding to the RMS are so small that they can not be seeing

In Fig. 2 we present the histogram of our observations of Nereid with respect to time. Each bar corresponds to one of the 11 observational missions made between 1993 - 1998.

We have the images of the type 1 for 4 images of 93, the first missions of 96, 97 and the first and second missions of 98. The mission of 94, the two missions of 95 and the second mission of 96 have images of type 2. For 5 images of the 93 mission, the third mission of 96 and the second of 97, we have images of type 3. The two image types in 1993 mission happens since, during the same night, we have frames where the image of Triton is measurable and others where it is not as explained above.

The distribution of all known positions on Nereid elliptic orbit is presented in Fig. 3. Our CCD observations are represented by circles and we can see that many of them were made at the periapsis region.

In Table 1 (accessible in electronic form) we list our positions of Nereid determined in equatorial coordinates. The data are presented in the following form: the first line gives the year, month and day and decimal fractions of UTC days, corresponding to the mean instant of the observation. In the next line we list the name of the satellite followed by the observed right ascension and the declination of Nereid. The reference system is referred to the equator and equinox of J2000.

In Table 2 (also accessible in electronic form) are presented our positions of Nereid referred to Triton. The presentation of the data follows that of Table 1 but the positions of Nereid are given by $(\alpha_{\mathrm{Nereid}} - \alpha_{\mathrm{Triton}})$ cos δ_{Triton} and $(\delta_{\mathrm{Nereid}} - \delta_{\mathrm{Triton}})$, where α_{Nereid} and α_{Triton} are the J2000 observed right ascensions of Nereid and Triton and δ_{Nereid} and δ_{Triton} are their observed declinations.

3. Calculation of the state vector for Nereid

By backwards numerical integration in time (Le Guyader 1993) which consider the barycenter of the Neptune - Triton system, the Sun and the eight other planets into the same reference frame used in Veiga et al. (1996), we have first computed the state vector of Nereid at Julian ephemeris date 2433007.5 (1949 April 1 at 0h TU). The starting constant values were here given by Jacobson et al. (1991) (here after called JRT) and issued from the DE403 Ephemeris. At each step-size of 0.5 day, the solutions were computed in Taylor series expansions of 19 derivatives with respect to time. Then, in order to fit these new positions and velocities of Nereid we have solved, by a least square method, a system of equations relating the

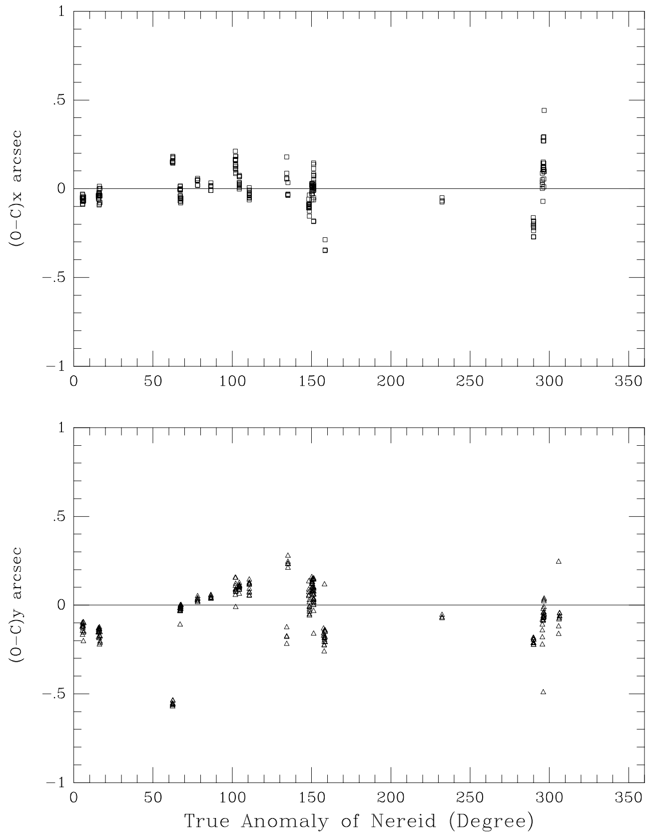

Fig. 7. O−C residuals of our CCD observations as function of the true anomaly

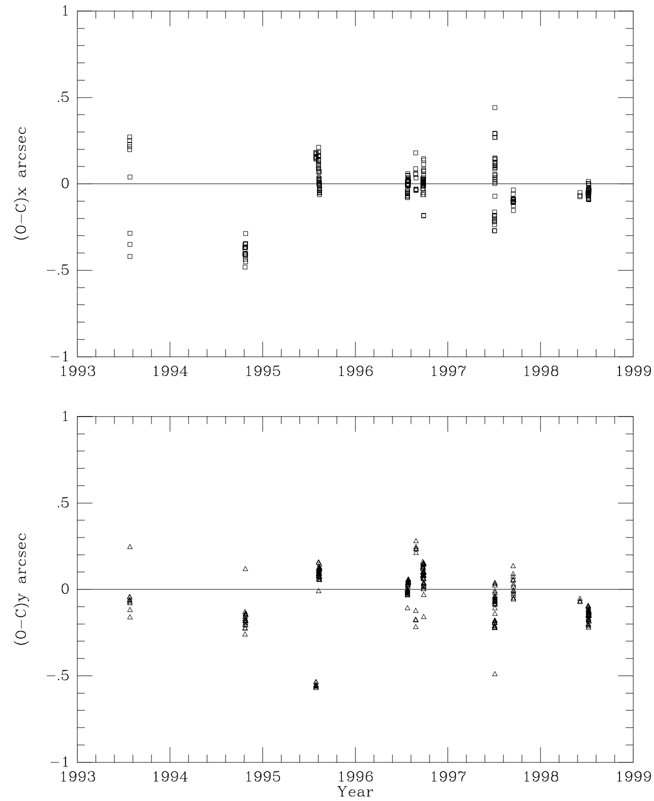

Fig. 8. O−C residuals of our CCD observations as function of time

unknown variations of the initial conditions with quantities (O−C), which are computed by 308 ground based observations and forwards numerical integration in time, up to the Julian ephemeris date 2450990.5. So after successive eliminating of 24 observations, the RMS for the remaining 284 (O−C) were $0\rlap{.}''23$ and $0\rlap{.}''22$ for the right ascension and declinations respectively. In Table 3 we present the fitted state vector of Nereid at Julian ephemeris date 2433007.5, and in Table 4 are listed the 24 eliminated observations.

The difference between the state vectors computed in JRT, is presented in Table 5. Its is given at Julian ephemeris date 2447680.5 and referred to the barycenter of the Neptunian system and to the equator and equinox J2000.0. Observe that the difference is about 0.1% of the state vector. This corroborate the good quality of the JRT state vector which fits well ours observations made up to nine years after its computation.

We can see in Fig. 3, that the set of observations are well distributed on the orbit and there are many positions near the periapsis. The observed minus calculated residuals for fitted observations as function of time are presented in Fig. 4. The residuals have a significant reduction for the observations made later than 1975. The same result is presented in Fig. 5, in this case referred to the true anomaly. As seen, the periapsis positions have small residuals.

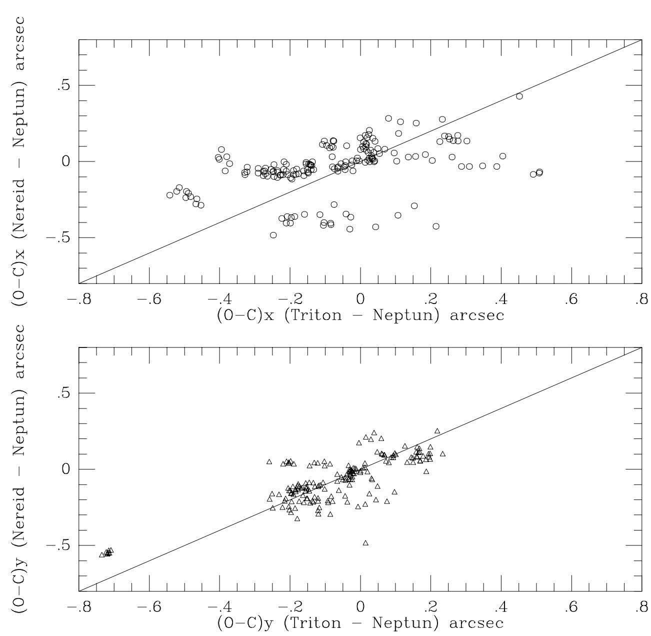

Fig. 9. Correlation between the residuals of Triton-Neptune and Nereid-Neptune. For Neptune it was taken the theoretical position given by DE403

Table 4. The 24 observations eliminated in our fitting. It is given the date for each observation. The first 23 positions are due to Van Briesbroeck and the last one to Werner Landgraf

	Observations	eliminated
5/ 1/1949	6/18/1949	4/18/1950
7/18/1950	1/ 5/1951	4/23/1952
7/ 3/1953	7/ 4/1953	7/ 5/1953
7/15/1953	2/ 5/1954	3/ 1/1954
4/21/1955	4/24/1955	4/ 6/1967
4/10/1967	5/14/1967	6/12/1967
3/31/1968	5/27/1968	4/22/1969
5/19/1969	6/18/1969	7/ 3/1987

Table 5. Difference between the state vectors computed in this paper and by JRT, at Julian ephemeris date 2447680.5. The reference system and units are the same as Table 3

Position (UA)	Velocity (UA/day)
9.06552234670315871E-6	−6.82890850823561144E-8
1.71186428784483868E-5	1.71572703889502284E-7
−1.04728233896126538E-5	−7.55289058513956835E-8

Table 6. The observed minus calculated RMS, means and standard deviations, in arcsecond, for the fitted and for our CCD observations

Number of Positions	Means and Standard deviations $\overline{(\mathrm{O-C})}_x$ $(\sigma)_x$	$\overline{(\mathrm{O-C})}_y$ $(\sigma)_y$
284 (1949-1998)	- (0.23)	- (0.22)
229 (1993-1998)	−0.02 (0.15)	−0.05 (0.16)

In Fig. 6 are presented the means and the errors for the fitted observations which were grouped by observer and opposition. The cases corresponding to only one or two observations are marked by triangles. The quality of the observations after 1980 is evident. The RMS for the observed minus calculated fitted observations and the means and the standard deviations for the fitted 284 positions and for our 229 observations are given in Table 6.

Table 7. Elliptical osculating elements of the orbit at Julian ephemeris date 2447680.5 referred to the barycenter of the Neptunian system and the mean equator and equinox J2000.0. In Col. 2 it is presented the osculating elements computed from our state vector and in Col. 3 the differences between our elements and those computed with the JRT state vector

Orbital elements	Osculating elements	Differences
a (UA)	6.68576536231141130	−0.377128953135685840E-7
e (radian)	0.754147151626165302	0.108270583104808082E-3
i (degree)	27.4803990159531857	0.528002817089159773E-2
Ω (degree)	353.053258620784050	−0.124291060833922828
ω (degree)	262.757323086024428	0.108622500977910458
$\dot{M}$ (degree/day)	0.999711644058355775	0.153436525738852718E-5
M (degree)	312.992795213609099	−0.525984946295743674E-2

In order to compare the orbits defined in this paper and in JRT, we list in Table 7 the elliptical osculating elements computed with our state vector and their differences from the Jacobson's osculating elements. As expected (see Table 5), the orbits are very similar.

4. Accuracy of our observations

Almost all published positions of Nereid are obtained from photographic plates. The only exception are four observations by Shaefer & Shaefer (1988). Therefore we will analyze in detail our CCD observations.

There are many differences among the photographic and the CCD observations (see for example Jones et al. 1998), the most important beeing the number of positions achieved in a night. While there is, in general, only one photographic position in a night, the number of CCD positions is larger than ten. For the periapsis region, the large number of observations is important since they correspond to different positions in the orbit and so represent a key contribution to the orbit determination. On the other hand, for every night, all positions in the apoapsis region are almost the same and their contribution for the orbit fitting is less important.

The variation of our positions in the orbit can be observed in Fig. 7 where the residuals are presented as function of the true anomaly. In Fig. 8, these same residuals are presented as function of the time. We can observe that the means are different of zero for every night with small scatter for some nights. In order to analyze the source of these errors we plotted the residuals of our measures of Triton-Neptune by Nereid-Neptune for x and y, which is presented in Fig. 9. For y, we observe that there is a good correlation between these two residuals pointing out that the astrometric reduction process is responsible for the errors in this direction. However for x direction, there is no clear correlation but we verify that the scatter is more important for the positions of Triton. Probably, this is due to the bad centering of the saturated and contaminated images of Triton in the direction of CCD columns which is the charges scattering direction.

Considering the image types we observe (Fig. 8) that the bad residuals appear, in general, for the images of the type 2 as expected. Regarding the number of stars used for the reduction of each image, we verified that the residuals that are far from the cluster corresponding to the observations in the same night, appear in the images where a few numbers of stars (about five) was used. This is the case of the four residuals of x and the 3 in y in 93 and one in y in 94. The small cluster in y direction, corresponding to the first mission in 95 is strongly correlated to the Triton residuals and so it is due to a bad astometric calibration of these images of type 2.

Therefore, we conclude that the behavior of the residuals is due to the astrometric reduction process.

5. Conclusion

We presented here a report of all our CCD observations taken in the last six years. These observations are part of a program started in 1982 to observe systematically the satellites of the planets with the 1.6 meter refractor of the Laboratório Nacional de Astrofísica in Brazil. In particular, for Nereid, 8 photographic positions were published in 1996. The large number and the good accuracy for our CCD observations confirms the adequacy of CCD observations to obtain the astrometric position of faint satellites far from its planet.

The good distribution of the positions on the elliptic orbit allows to a fit of the orbit, which is very similar to JRT orbit. It will can be used in a future determination of the parametrs in an analytical theory of Nereid's motion.

Acknowledgements. We want to thank A.H. Andrei, for their help in this work and the staff of Laboratório Nacional de Astrofísica for the assistance during our observations. We thanks J. Berthier and P. Bretagnon for their help in the calculation of the state vector for Nereid. We thanks also Ch. Veillet by the sugestions in the final version of this paper, manly for the accuracy study. C.H. Veiga and R. Vieira Martins thanks the CNPq-Brazil for partial support of this work.

References

Assafin M., Vieira Martins R., Andrei A.H., 1997a, AJ 113, 1451
Assafin M., Vieira Martins R., Andrei A.H., Veiga C.H., 1997b, AJ 113, 2329
Assafin M., Vieira Martins R., Andrei A.H., 1997c, in Proceedings of the ESA Symposium "Hipparcos - Venice '97", pp. 181-183
Colas F., Serrau M., 1993, Astrol and Interpol version 3.10. Édition du Bureau des Longitudes, Paris, France
Jacobson R.A., 1990, A&A 231, 241
Jacobson R.A., Reidel J.E., Taylor A.H., 1991, A&A 247, 563
Jones D.H.P., Taylor D.B., Williams I.P., 1998, A&A 130, 77
Kuiper G.P., 1949, PASP 61, 175
Landgraf W., 1988, IAUC 4542
Le Guyader Cl., 1993, A&A 272, 687
Mignard F., 1975, A&A 43, 359
Mignard F., 1981, AJ 86, 1728
Rose L.E., 1974, AJ 79, 489
Schaefer M.W., Schaefer B.E., 1988, Nat 333, 436
Standish E.M., Newhall X.X., Williams J.G., Folkener W.P., 1995, JPL Planetary and Lunar Ephemerides DE403/LE403, JPL IOM 314.10-127
Van Biesbroeck G., Vesely C.D., Aksnes K., Marsden B.G., 1976, AJ 81, 122
Veillet C., 1982, A&A 112, 277
Veillet C., Bois E., 1988, A&A 189, 303
Veiga C.H., Vieira Martins R., Le Guyader Cl., Assafin M., 1996, A&AS 115, 319
Vieira Martins R., 1989, in Orbital Dynamics of Natural and Artificial Objects, Vieira Martins R., Lazzaro D., Sessin W. (eds.). Observatorio Nacional, Rio de Janeiro, pp. 59-70
Vieira Martins R., Veiga C.H., Assafin M., 1996, in Dynamics, Ephemerides and Astrometry of the Solar System, Ferraz-Mello S., Morando B. and Arlot J.E. (eds.). Kluwer, Dordrecht, pp. 419-422