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Nereid's orbit based on new precise observations

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Abstract A new orbit of Triton was provided by our previous work, benefitted by new Gaia Data, both in a new precise reduction of charge-coupled device observations and in the planetary ephemeris INPOP19a. In this paper, we provide a new ephemeris for another main Neptunian satellite, Nereid. The orbit is fitted for the newest observations, including $2\,075$ ground-based observations during the period 1949-2018 and 83 space observations acquired by the Voyager 2 spacecraft in 1989. The dynamical model used here is consistent with that of our previous work. For the ground-based absolute observations of Nereid, the root-mean-square deviations are $0.201''$ in right ascension and $0.189''$ in declination. Finally, a comparison with the HORIZONS ephemeris is made and discussed.

Key words: astrometry — celestial mechanics — ephemerides — planets and satellites: individual (Nereid)

1 INTRODUCTION

The distant satellites of major planets are of great interest to the dynamics of the Solar System. Knowledge of the orbits of these satellites helps to establish a picture of the evolution of the system and provides information to confirm hypotheses about the origin of satellites (Emelyanov 2020). As a distant satellite of the Neptune, Nereid was discovered in 1949 and has many photographic and charge-coupled device (CCD) observations. These observations help us to investigate the orbital evolution of Nereid.

Distant satellites of the planets are subject to strong perturbations from the Sun. The determination of these perturbations by analytical methods is very difficult, although such attempts have been made in past centuries (Emelyanov 2020). Numerical methods would be generally adopted to refine the orbits. After the close detection of the Neptunian system by the Voyager 2 spacecraft, the precise numerical models of Nereid were provided by Jacobson (2009) and Emelyanov & Arlot (2011). The ephemerides are available on HORIZONS (Jet Propulsion Laboratory) ephemeris sever[1] and MULTI-SAT ephemeris computation facility[2] (Emel'Yanov & Arlot 2008).

The property of Neptune's satellite system is special. Neptune has only one massive satellite Triton, which has strong effects on the Neptune and Neptune's pole. Whereas other Neptunian satellites are small and their masses unknown. For this reason, Nereid could be assumed to be massless during the related calculations (Jacobson 2009). Lately, we have obtained a new ephemeris of Triton (Tang et al. 2020), with new precise observations and the INPOP19a ephemeris. The orientation of Neptune's pole was obtained simultaneously as the calculation of Triton's motion. A comparison with Jacobson (2009)'s solution was made and discussed, in particular the influence of using different planetary ephemerides. We will continue to develop a new model of Nereid's motion, based on the dynamical model and the orbit of Triton from Tang et al. (2020).

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[1] `https://ssd.jpl.nasa.gov/horizons.cgi`
[2] `http://www.imcce.fr/sat`

In addition, the Gaia Data Releases (DR) provide a great many reference stars with high precise positions and proper motions. The usage of this high-quality Gaia catalogue improves the precision of observation reduction. Even for early Nereid's observations, the precision could be more than doubled after re-reduction (Yu et al. 2019). In this paper, we will use these new precise positions of Nereid to refine its orbit.

A new ephemeris of Nereid is provided in this paper. Section 2 introduces the numerical model used for the calculations of Nereid's motion. The ground-based observations during 1949-2018 and the Voyager 2 observations are used and addressed in Section 3. Section 4 is about the Nereid's refined orbit, and a comparison with the HORIZONS ephemeris to assess the accuracy of our result.

2 NUMERICAL MODEL

In Tang et al. (2020), the orbit of Triton was obtained by numerical integration in a Neptunian barycentric reference system (NBRS), whose axes are aligned parallel to those of the International Celestial Reference Frame. The coordinate time is Barycentric dynamical time (TDB). Now our calculations of the Nereid's motion are still performed in this NBRS. The dynamical model and numerical integrator used here are almost the same as Tang et al. (2020). We thus refer to Tang et al. (2020) for a detailed description.

In our dynamical model, Nereid was treated as a massless object. The equations of motion included contributions from the gravitational effects of the Neptune, Triton, the Sun, and other planets in the Solar System. The second and fourth zonal harmonic perturbations from the Neptune were taken into account. The motion of Neptune's rotation axis was considered. We employed the model of Neptune's pole from Tang et al. (2020). The key difference in the dynamical model with other theories is about the motion of Neptune's pole: Emelyanov & Arlot (2011) assumed that the pole is fixed; Jacobson (2009) obtained the orientation of the pole through the constant total angular momentum; Tang et al. (2020) integrated the simplified Euler's equations of motion directly.

The differential equations of Nereid's motion were integrated using the Bulirsh-Stoer scheme, with 0.1-days step size. The positions of the Sun and planets in the Solar System were provided by the INPOP19a ephemeris (Fienga et al. 2019). The position of Triton and the orientation of Neptune's pole were calculated during the integration, the same as Tang et al. (2020). Other dynamical parameters are displayed in Table 1.

Table 1 Dynamical Parameters (Referred to Jacobson 2009)

No.	Name	Value	Unit
1	GM (Neptunian System)	6 836 527.10058	$\mathrm{km^3s^{-2}}$
2	GM (Triton)	1427.59814	$\mathrm{km^3s^{-2}}$
3	Neptune J_2	3408.43×10^{-6}	
4	Neptune J_4	-33.40×10^{-6}	
5	Neptune radius	25 255	km

3 OBSERVATIONS

Nereid was discovered in 1949. It is one of Neptune's distant satellites, with a semi-major axis of $5\,513\,400\,\mathrm{km}$. Albeit faint with a magnitude of 19, Nereid has many photographic and CCD observations. Thanks to the new Gaia catalogue, an increasing number of precise Nereid's positions would be available. For the latest observations which were reduced using the Gaia DR1, the precision could reach $70\,\mathrm{mas}$ (Yu et al. 2018).

To fit Nereid's orbit, we used the ground-based observations since the discovery year and till 2018, which are available from the Natural Satellites Data Center[3] (NSDC; Arlot & Emelyanov 2009), and the Voyager 2 observations from Jacobson (1991). The details of all the observations are listed in Table 2. The data consist of absolute observations: right ascension and declination; the relative observations that measure the coordinate differences between Neptune and Nereid, denoted by X and Y.

Compared with the work of Emelyanov & Arlot (2011), new observations were added, including: (1) the observations from the European Southern Observatory, La Silla and the Observatory do Pico dos Dias, Itajuba (1992–2014; Gomes-Júnior et al. 2015); (2) the observations from the Xinglong Observatory of the National Astronomical Observatories, Chinese Academy of Sciences (NAOC) (2006–2007; Qiao et al. 2008), which were re-reduced by Yu et al. (2019) using the Gaia DR2; (3) the observations from the Xinglong Observatory of NAOC and the Lijiang Observatory of Yunnan Observatories, Chinese Academy of Sciences (2012–2017; Yu et al. 2018), reduced with the Gaia DR1; (4) the observations published in Minor Planets Circulars (MPC) from 2011–2018.

The observations used in this work include the data published in MPC Nos. 43261, 46508, 49424, 52492, 52493, 52887, 53171, 57110, 57416, 57417, 59029, 57573, 57792, 57947, 58097, 59581, 59860, 60086, 60268, 60451, 60647, 60906, 61163 62864, 63363, 63584, 63806, 64093, 65920, 66450, 66686, 66905, 67130, 67668, 70193, 71528, 72437, 75593, 75849, 76329, 76732, 79140, 79746, 79971, 80114, 80452, 83713, 84214, 84512, 84739, 85079, 85502,

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[3] `http://nsdb.imcce.fr/`

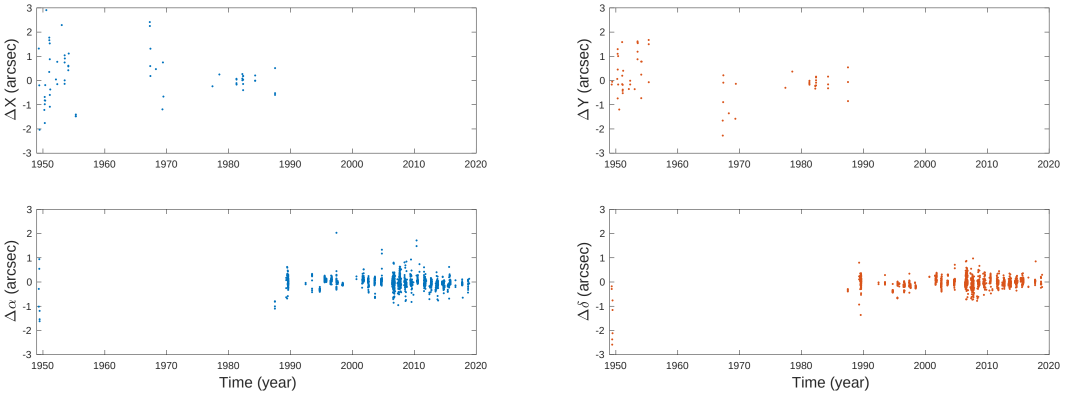

Fig. 1 Residuals for all types of observations during the period 1949–2018.

Table 2 Nereid observation residuals (1949–2018). The unit of the residuals is arcsecond.

k	Date	Observatory code	Source	Type	Num	RMS1	RMS2
1	1949–1949	711	Harris & van Biesbroeck (1949)	α,δ	7	1.116	1.640
2	1949–1951	711	van Biesbroeck (1951)	X,Y	19	1.309	0.998
3	1952–1955	711	van Biesbroeck (1957)	X,Y	16	1.025	1.025
4	1967–1969	711	Rose (1974)	X,Y	9	1.319	1.633
5	1977–1981	711,809	Veillet (1982)	X,Y	6	0.166	0.215
6	1982–1984	568,809	Veillet & Bois (1988)	X,Y	11	0.183	0.204
7	1987–1987	807	Schaefer & Schaefer (1988)	α,δ	4	0.938	0.343
8	1987–1987	809	Landgraf (1988)	X,Y	3	0.544	0.584
9	1989–1989	Voyager 2	Jacobson (1991)	α,δ	83	0.226	0.268
10	1992–2014	809,874	Gomes-Júnior et al. (2015)	α,δ	873	0.126	0.098
11	1993–1998	874	Veiga et al. (1999)	α,δ	229	0.209	0.217
12	2000–2010	511	Emelyanov & Arlot (2011)	α,δ	140	0.118	0.148
13	2001–2006	213,415,568,644,807,D35	MPC	α,δ	119	0.350	0.287
14	2006–2007	327	Yu et al. (2019)	α,δ	140	0.072	0.085
15	2007–2010	415,673	MPC	α,δ	114	0.396	0.340
16	2011–2016	673,C95,E07,F51,G37,G40,W84	MPC	α,δ	220	0.198	0.142
17	2012–2017	327,O44	Yu et al. (2018)	α,δ	150	0.072	0.071
18	2017–2018	D29,G40,I41,Z80	MPC	α,δ	15	0.243	0.266

89137, 89456, 90446, 90966, 94830, 95374, 97001, 99414, 100688, 100689, 101342, 107170, 110808, 112835, and 115989.

In all, 2084 ground-based observations during 1949–2018 and 83 Voyager 2 observations were acquired. Nine of ground-based observations were rejected judging by the three-sigma rule for outlier detection. The rest were used for the next process of orbit refinement.

Table 3 Nereid's state vectors at Julian day $2\,447\,763.5$ (TDB), with respect to the NBRS.

Position (km)	Velocity ($\mathrm{km\,s^{-1}}$)
4150051.17004046	0.470727692999158
1780641.3474918	1.06368344482533
1185064.98826876	0.579296053616574

4 NEREID'S ORBIT

The least-squares method was used to refine the initial condition of Nereid's orbit, which was from Jacobson et al. (1991). The initial date for the integration of Nereid's orbit was set to Julian day $2\,447\,763.5$ (TDB), when Voyager 2 closely detected the Neptune. After six iterations, we obtained the final values of the Nereid's epoch state vectors (see Table 3), with respect to the NBRS. The residuals of all the observation sets are depicted in Figure 1 for different types and are also presented in Table 2. The last two columns of Table 2 give the root-mean-square (RMS) of the observation residuals. For the ground-based absolute observations of Nereid, the RMS deviations are $0.201''$ in right ascension and $0.189''$ in declination. Specially for the observations which were reduced using the Gaia star catalogue, the dispersions of them are around $70-80$ mas (Yu et al. 2018, 2019). Our Nereid's orbit can be reconciled with these observations. This orbit was fit to Chebychev polynomials. The source is available on request through email.

To check our Nereid's orbit, we made a comparison with the ephemeris of the HORIZONS system (Giorgini et al. 1996). Now the Nereid's model in HORIZONS system has been updated to the NEP096

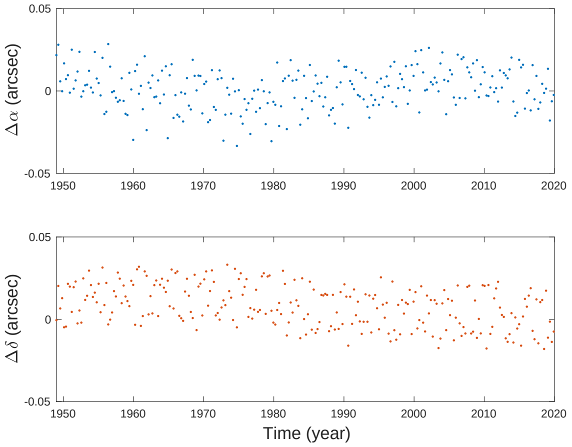

Fig. 2 Differences between our result and the result from the HORIZONS system in right ascension (*top panel*) and declination (*bottom panel*) of Nereid during the period 1949–2018.

version, and the model for the planets adopts the DE431 planetary ephemeris solution. To avoid the deviations from different planetary ephemerides, we use the DE431 ephemeris (Folkner et al. 2014) to compute the coordinates of Neptune in this comparison. Figure 2 plots the differences in absolute position between these two results. These differences could be attributed to the different dynamical models, observations or data-weighing strategies. Even so, the deviations do not exceed $0.05''$ both in right ascension and declination. It supports our result in Tang et al. (2020) again. Although the different planetary ephemerides have large differences in Neptune's position, the orbits of Nereid using different planetary ephemerides are still close, under similar dynamical models.

5 DISCUSSION

We constructed a new numerical model of Nereid's motion in this paper. This model is based on the dynamical of the Neptunian system in Tang et al. (2020), where the orientation of Neptune's pole in particular was obtained by integrating simplified Euler's equations of motion. The INPOP19a ephemeris was used to compute the coordinates of the Sun and planets in the Solar System. The positions of Triton were the same as Tang et al. (2020) to calculate its gravitational perturbation. In our work, 2 075 ground-based observations during the period 1949–2018 and 83 Voyager 2 observations were fitted.

The least-squares method was used to refine the initial condition of Nereid's orbit. A new orbit of Nereid was obtained here. The RMS deviations of the absolute ground-based observations are $0.201''$ in right ascension and $0.189''$ in declination. Comparing our result with the ephemeris from the HORIZONS system, the deviations do not exceed $0.05''$ in right ascension and declination during the period 1949–2018. Our orbit is closed to the JPL-NEP096 solution.

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