ARTICLE IN PRESS

Planetary and Space Science xxx (2017) 1–4

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

New precise astrometric observations of Nereid in 2012–2017

Y. Yu[a,b,*], R.C. Qiao[c], D. Yan[d], X. Cheng[c], X.J. Xi[b,c,e], K. Tang[a], H. Luo[a]

[a] Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai, 200030, China
[b] School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing, 100049, China
[c] National Time Service Center, Chinese Academy of Sciences, Lintong, Shaanxi, 710600, China
[d] School of Electronic Information, Huanggang Normal University, Huanggang, 438000, China
[e] Institute for Celestial Mechanics and Computation of Ephemerides, Paris Observatory, IMCCE, F-75014, Paris, France

ARTICLE INFO

Keywords:
Astrometry–planets and satellites
General–methods
Observational

ABSTRACT

Nereid is one of the most distinctive natural satellites that we know in the Solar system. The orbit of Nereid is highly eccentric and inclined with respect to the equator of its primary, Neptune. Studying Nereid is one of the inspiring ways to acquire better knowledge of the Solar system. Due to its faintness, the ground-based observations of Nereid have been limited and the observation precisions in the past were generally not high. A total of 150 new observed positions of Nereid in the period 2012–2017 were collected by the 0.8 m reflecting telescope at Xinglong station of National Astronomical Observatory and the 2.4 m reflecting telescope at Lijiang station of Yunnan Astronomical Observatory. Thanks to the high-quality reference catalogue Gaia DR1 and suitable processing methods for images, the precision of our new observations of Nereid is 2–3 times higher than those of the previous observations, and the dispersions of our observations are better than 70 mas.

1. Introduction

Nereid, the second satellite of Neptune, was discovered in 1949 by Gerard P. Kuiper using the 82-inch telescope at the McDonald observatory. Nereid is one of the most distinctive satellites that we know in the Solar system. The orbit of Nereid has a high eccentricity of about 0.75 and a large inclination of about 27° with respect to Neptune's equator. The orbital period is about 360 day. The unusual orbit of Nereid suggests that it may be either a captured asteroid or Kuiper belt object, or it was an inner moon in the past and but was perturbed during the capture of Neptune's largest satellite Triton (Brown et al., 1998). Because of these distinct characteristics, the study of Nereid may shed light on the formation and evolution of the Solar system. Nereid is very faint with a visual magnitude m_v of 19 even during the opposition of Neptune, which usually makes the ground-based observations difficult. Therefore, the ground-based observations of Nereid have been few and the observation precisions in the past were generally not high, only 0.1–0.2 arcsecond (Veiga et al., 1999; Qiao et al., 2008; Gomes Junior et al., 2015).

The continuous and accurate astrometric observations of the satellites are necessary for the analysis of long-term physical elements, such as the establishment of accurate dynamical models (Arlot et al., 2012). We have been performing CCD astrometric observations of Nereid since 2006. In the period 2012–2017, we observed Nereid using the 0.8 m reflecting telescope at Xinglong station of National Astronomical Observatory (IAU code number 327) and the 2.4 m reflecting telescope at Lijiang station of Yunnan Astronomical Observatory (IAU code number O44). A total of 150 new observed positions of Nereid were measured with respect to the stars in Gaia DR1 star catalogue (Gaia Collaboration et al., 2016a, b). In this paper, we discuss the facilities and procedures of the observations, as well as methods of data reduction (Section 2). We also analyze the precisions of the new observations and compare the results with previous works (Sections 3). Finally, we draw a conclusion (Section 4).

2. Observations and reduction

2.1. Observations

We carried out successive CCD astrometric observations of Nereid during the oppositions of Neptune in September 2012, October 2013, October 2015, and September 2017. The observations in 2012 were made with the 0.8 m reflecting telescope at Xinglong station of National Astronomical Observatory (117°.577 E, 40°.396 N, H940m). The 0.8 m reflecting telescope was equipped with a CCD chip of 1 340 × 1 300 pixels corresponding to a field of view of about 11 × 11 arcmin^2. The latter three sets of observations were made with the 2.4 m reflecting telescope at the Lijiang station of Yunnan Astronomical Observatory

* Corresponding author. 80 Nandan Road, Shanghai 200030, China.
E-mail address: yuy@shao.ac.cn (Y. Yu).

https://doi.org/10.1016/j.pss.2018.01.001
Received 28 November 2017; Received in revised form 29 December 2017; Accepted 8 January 2018
Available online xxxx
0032-0633/

Please cite this article in press as: Yu, Y., et al., New precise astrometric observations of Nereid in 2012–2017, Planetary and Space Science (2017), https://doi.org/10.1016/j.pss.2018.01.001

Table 1
Specifications of the telescopes and CCD chips used for the observations of Nereid.

Year	2012	2013	2015, 2017
Site code	327	O44	O44
Diameter of primary mirror	0.8 m	2.4 m	2.4 m
Focal length	8 000 mm	19 200 mm	9 375 mm
Size of CCD array (pixels)	1 340 × 1 300	1 340 1 300	2 148 × 2 200
Size of pixel	20 μm	20 μm	13.5 μm
Angular extent per pixel	0.52 arcsec	0.21 arcsec	0.30 arcsec
Field of view	11 × 11 arcmin^2	4.7 × 4.7 arcmin^2	10.5 × 10.5 arcmin^2

Table 2
Means of the standard deviations σ_0 for the reduction with various models.

Observation set	σ_0 (arcsecond)			
	1-order	2-order	3-order	4-order
80	0.097	0.100	0.104	0.106
240a	0.062	0.065	0.073	0.070
240b	0.118	0.113	0.069	0.067
240c	0.119	0.112	0.087	0.088

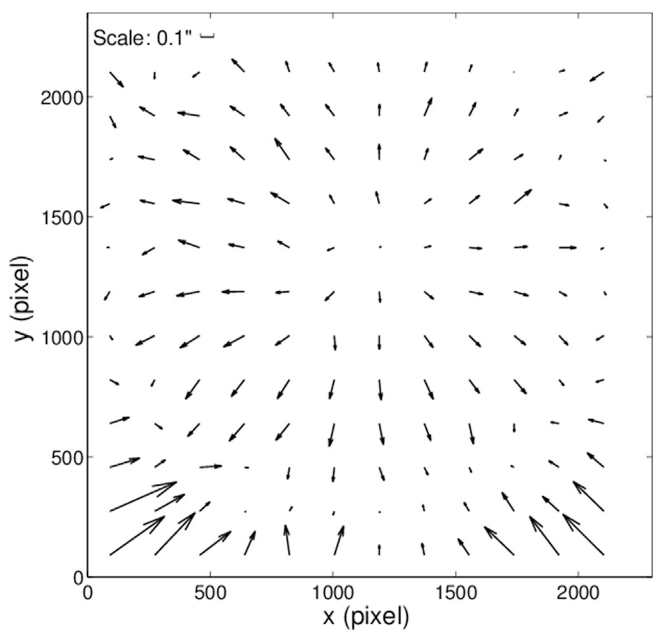

Fig. 1. Distortion pattern of the CCD field of view for the observations of set 240c.

(100°.031 E, 26°.709 N, H3193m). For the observations in 2013, the 2.4 m telescope was used, which was equipped with a CCD chip of 1 340 × 1 300 pixels corresponding to a field of view of about 4.7 × 4.7 arcmin^2; for the observations in 2015 and 2017, the CCD chip was replaced by a CCD chip of 2 148 × 2 200 pixels, and the field of view was expanded to 10.5 × 10.5 arcmin^2 by using a focus reducer. More information about the instruments and their CCD chips is listed in Table 1. Taking into account the faintness of the Nereid, we did not use filters during all our observations. According to standard procedure of astrometric observation, the flat-field images were taken at dusk and dawn respectively. The bias-field images were taken at the beginning and at the end of the observation. The dark-field images were taken only at the end. The exposure time was about 1–10 min, depending on the setting of different telescopes, the weather conditions and the elevation above horizon of the observed objects.

A total of 150 new astrometric positions of Nereid were obtained in the period 2012–2017. For the first set, in September 2012 (set 80), we obtained 24 positions with the 0.8 m reflecting telescope. Next, in October 2013, October 2015 and September 2017, we obtained 29 positions (set 240a), 72 positions (set 240b) and 25 positions (set 240c), with the 2.4 m reflecting telescope respectively.

2.2. Reduction

The darker a signal the telescope can detect, the more stars can be observed. The brightness of Nereid is close to 19 mag, once it is successfully observed, a considerable number of stars can be observed simultaneously in the field of view. When the newly released Gaia DR1 star catalogue is chosen as the reference star catalogue, almost all the stars in the field of view can be used in the calculation of the plate model. As the 4 sets of observations were made near the epoch J2015.0 of Gaia DR1, the effect of proper motions for stars could be neglected.

In order to improve astrometric precisions of Nereid, it is necessary to adopt the appropriate plate model or processing method to describe the imaging pattern of the telescope accurately. Based on CCD observations of natural satellite, the imaging pattern can be determined as follows. First, we calculated the observed position for each star according to standard astrometric procedures, aiming to remove the relative position change among stars caused by the astronomical factors, such as differential atmospheric refraction and differential light aberration. Second, we calculated the standard coordinates (ξ, η) for each stars according to the rule of gnomonic projection. Third, we fitted the relationship between standard and measured coordinates with various plate models, which is equivalent to using the stellar frame to examine the imaging pattern of the measured coordinate system. Last, we judged which model yielded the best result based on the standard deviations of the postfit residuals and the number of model order used. Usually it was the model with the least number of order among those of the smallest standard deviation within the range of error. To this end, for each set of observations, we used 1-, 2-, 3- and 4- order plate model (i.e. 6-, 12-, 20- and 30- parameter model) to perform the reduction. Table 2 lists the means of the standard deviations with various models.

It can be seen that for the observations of set 80 and set 240a, the standard deviations of 1-order model are on the same level as those of the nonlinear models, which indicates that the imaging pattern of set 80 and set 240a can be described appropriately by the linear model. While for the 2.4 m reflecting telescope at Lijiang station, due to the use of the focus reducer, the imaging pattern shows the nonlinear characteristics. From the results of set 240b and set 240c in Table 2, it is shown that until the 3-order model is adopted, the standard deviations are comparable to those of higher order models. For a CCD field of view with nonlinear imaging pattern, the ideal processing scheme is to make the distortion correction for each CCD image first, and then to perform the calculation of the plate model. When the precision of star catalogues was not high enough, Peng et al. (2012) proposed an effective approach of measuring distortion of a CCD field of view based on the dithered observational scheme and has applied to the reduction of the observations made with the 2.4 m reflecting telescope (Peng et al., 2015). With Gaia DR1 star catalogue released, the calibration of field distortion becomes more convenient. During the observations period of Set 240c, we also observed the regions of open cluster NGC7209 with a large number of stars. A total of 30 CCD images were taken and there are about 300–400 stars evenly distributed on each image. The distortion pattern of the CCD field of view can be determined by the statistics of the residuals of Gaia DR1 stars reduced with 1-order model, as shown in Fig. 1. It can be seen that the largest distortion vectors are about 0.5 arcsecond at the corner of the field of view. We applied the distortion pattern to the measured coordinates of the stars of set 240c to remove the effect of field distortion, and then the positions of Nereid were calculated with the linear model. At this time, the standard deviations of the reference stars are about 0.084 arcsecond,