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Preliminary results of CCD observations targeting Himalia acquired at Yunnan Observatories in 2015

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Abstract In order to study the potential associated with high precision CCD astrometry of irregular satellites, we have acquired experimental observations of Himalia, the sixth and irregular satellite of Jupiter. A total of 185 CCD observations were obtained by using the 2.4 m and 1 m telescopes administered by Yunnan Observatories over ten nights. Preliminary analysis of the observations were made, including geometric distortion, atmospheric refraction, and also the phase effect. All positions of Himalia are measured relative to the reference stars from the catalog UCAC4 in each CCD field of view. The theoretical positions of Himalia were retrieved from the Institute de Méchanique Céleste et de Calcul des Éphémérides, while the positions of Jupiter were obtained based on the planetary ephemeris INPOP13c. The results show that the means of observed minus computed $(O-C)$ residuals are $-0.004''$ and $-0.002''$ in right ascension and declination, respectively. The standard deviations of $(O-C)$ residuals are estimated to be about $0.04''$ in each direction.

Key words: astrometry — planets and satellites: individual (Himalia) — methods: observational

1 INTRODUCTION

Irregular satellites are natural moons of giant planets in our solar system. However, unlike regular moons, these irregular satellites are smaller and have more distant, highly eccentric, and highly inclined orbits (Nicholson et al. 2008; Grav et al. 2015). It is widely accepted that these objects are closely related to early solar system formation, because they are believed to have been heliocentric asteroids before being captured by a giant planet's gravity (Colombo & Franklin 1971; Heppenheimer & Porco 1977; Pollack et al. 1979; Sheppard & Jewitt 2003; Agnor & Hamilton 2006; Nesvorný et al. 2007, Nesvorný et al. (2014)). In order to further understand their dynamics and physics, routine observations, both from the Earth and from spacecraft, are needed (Jacobson et al. 2012). In comparison with regular ones, the ephemerides of irregular satellites have relatively worse precision. Thus, lots of high precision astrometric observations are required to improve their ephemerides.

Himalia is the largest member of the Jovian outer irregular satellite system (Grav et al. 2015). It was discovered by Perrine at Lick Observatory in 1904 (Perrine 1905). Continuous observations were made after its discovery, including the first computation of diameter, 170 ± 20 km, by Cruikshank (1977). When high precision space observations were made after Himalia was first visited in a flyby by the Cassini space probe in 2000 (Porco et al. 2003), long-term CCD observations of ground-based telescopes have been obtained and they also show great potential in deriving high precision positions for irregular satellites (Gomes-Júnior et al. 2015). In our recent research work on Phoebe, the ninth and irregular satellite of Saturn, positional precision of $0.04''$ in each direction was obtained (Peng et al. 2015). In order to obtain high precision astrometric results, a series of error effects should be taken into account, especially geometric distortion (called GD hereafter). Previous research works (Peng et al. 2012; Zhang et al. 2012) have shown obvious GD effects in the CCD field of view of the 2.4 m and 1 m telescopes administered by Yunnan Observatories. More recent research works (Peng et al. 2015; Wang et al. 2015) have again confirmed these GD effects.

The contents of this paper are arranged as follows. In Section 2, the astrometric observations are described. Section 3 presents details on the reduction of the observations and Section 4 provides the results. In Section 5, we provide discussions. Finally, the conclusions are drawn in Section 6.

2 ASTROMETRIC OBSERVATIONS

Astrometric observations of Himalia were carried out over ten nights in 2015 using two telescopes administered by Yunnan Observatories. Specifically, eight nights of CCD observations were made by the Yunnan Faint Object Spectrograph and Camera (YFOSC) instrument attached to the 2.4 m telescope (longitude E $100°1'51''$, latitude N $26°42'32''$, height 3193 m above sea level), and two nights of CCD observations were made by the 1 m telescope (longitude E $102°47'18''$, latitude N $25°1'46''$, height 2000 m above sea level). The detailed specifications of the two telescopes and CCD detectors are listed in Table 1. The observational dates were chosen according to the epoch when Jupiter was at opposition, which was 2015 February 6. However, no observations were made from February 1 to February 6, because the Jovian system was very close to the Moon in the sky.

A total of 185 CCD frames targeting Himalia were obtained, as well as 280 CCD frames of calibration fields. Details on the distribution of observations with respect to the observational dates for the two telescopes are listed in Table 2. It can be seen that 151 CCD frames of Himalia were obtained from the 2.4 m telescope, and 34 CCD frames of Himalia were obtained with the 1 m telescope. The exposure time for each CCD frame ranged from 18 s to 120 s, depending on the diameter of the primary mirror and meteorological conditions. Calibration fields were observed by following Himalia, except for four nights when the observations were acquired during rapidly changing weather conditions.

3 REDUCTION OF THE OBSERVATIONS

After the preprocessing steps including bias and flat correction were performed, image centering was applied by using the two-dimensional Gaussian fit algorithm (Li et al. 2009). The same procedure was used to process CCD frames of calibration fields which are open clusters, and then the GD patterns were derived. More details about how the GD patterns were derived are presented in Peng et al. (2012). Figure 1 shows the GD patterns for the 2.4 m and 1 m telescopes.

As mentioned above, the calibration fields were not observed on every night. GD corrections were applied on each night if the GD pattern was available, otherwise the GD pattern of the nearest night was used. Furthermore, we have conducted several experiments using the CCD frames of Himalia obtained with the 2.4 m telescope. GD corrections were applied by using only one of the GD patterns in each of the experiments. The results showed that the absolute difference in positional measurement made when using a GD pattern from another night is within $0.005''$. More details are presented in our previous research work (Wang et al. 2015), in which the influence of using different GD schemes on $(O-C)$ residuals was studied.

The catalog UCAC4 (Zacharias et al. 2013) was chosen to match reference stars in all CCD frames. The minimum and maximum numbers of UCAC4 reference stars available for Himalia astrometric reduction from observations made with the 2.4 m telescope are 7 and 19, respectively. For observations made with the 1 m telescope, these two numbers are 5 and 9, respectively. Observed positions of Himalia were derived relative to these UCAC4 reference stars by using a plate model with four constants. However, this is only accurate after all the astrometric effects, including GD effects, are taken into account (Peng et al. 2012).

According to the illustration presented in Lindegren (1977), the phase effect has a direct influence on positional measurements of planets and natural satellites in our solar system. Phase corrections should be considered and applied for these objects. By using equation (14) presented in Lindegren (1977), the phase effect of Himalia is calculated. Table 3 shows the details. It can be seen that the maximum value of the phase effect according to the observation time is as small as $0.0005''$. This means the phase effect of Himalia in our observations is negligible.

The IAU-SOFA (Standards of Fundamental Astronomy) library (Wallace 1996) is used to calculate the topocentric apparent positions of the reference stars in all CCD frames. The IAU 2006/2000A precession-nutation models (Capitaine & Wallace 2006) are used in the calculations. In order to derive the GD patterns accurately, the atmospheric refraction effect (the standard model should be precise enough, Peng et al. 2012) is added to the positional reduction of reference stars.

4 RESULTS

The observed positions of Himalia were compared to the ephemerides retrieved from Institute de Méchanique Céleste et de Calcul des Éphémérides which include satellite theory by Emelyanov (2005), and the theoretical positions of Jupiter were obtained by using planetary ephemeris INPOP13c (Fienga et al. 2014). For comparison, the ephemeris computed by the Jet Propulsion Laboratory (JPL) Horizons ephemeris service (Giorgini et al. 1996) was also obtained, including the satellite theory JUP300 (Jacobson 2013) and planetary theory DE431 (Folkner et al. 2014).

Figure 2 shows the $(O-C)$ residuals of the positions for Himalia expressed in terms of observational epochs.

Table 4 lists the statistics of $(O-C)$ residuals for Himalia before and after GD corrections. It can be seen that the internal agreement or precision for an individual night has been significantly improved after GD corrections for the 2.4 m telescope, but the results slightly changed for the 1 m telescope. This is due to the GD effect associated with the 1 m telescope being quite smaller than the 2.4 m telescope, as shown in Figure 1. The means of $(O-C)$ residuals for all data sets after GD corrections are $-0.004''$ and $-0.002''$ in right ascension and declination, respectively.

Table 1 Specifications of the 2.4 m and 1 m telescopes administered by Yunnan Observatories and their corresponding CCD detectors.

Parameters (1)	2.4 m telescope (2)	1 m telescope (3)
Approximate focal length	1920 cm	1330 cm
F-ratio	8	13
Diameter of primary mirror	242 cm	102 cm
CCD field of view (effective)	$9' \times 9'$	$7' \times 7'$
Size of CCD array (effective)	1900×1900	2048×2048
Size of pixel	$13.5\,\mu m \times 13.5\,\mu m$	$13.5\,\mu m \times 13.5\,\mu m$
Approximate angular extent per pixel	$0.286''$/pixel	$0.209''$/pixel

Notes: Column (1) shows the parameters and the following columns list their values for the two telescopes.

Table 2 CCD observations of Himalia and calibration fields using the 2.4 m and 1 m telescopes at Yunnan Observatories.

Observation Dates (1)	Calibration fields Dense star fields (2)	No. and filter (3)	Himalia No. and filter (4)	Telescope (5)
2015–01–31	NGC 1664	44I	21I	2.4 m
2015–02–07	NGC 2324	44I	25I	2.4 m
2015–02–08	NGC 2324	44I	14I	2.4 m
2015–02–09	NGC 2324	44I	18I	2.4 m
2015–02–10	NGC 1664	44I	18I	2.4 m
2015–02–11			18I	2.4 m
2015–02–12			18I	2.4 m
2015–02–13			19I	2.4 m
2015–02–12	M35	60I	14I	1 m
2015–02–14			20I	1 m
Total		280I	185I	

Notes: Column (1) shows the observational dates. Column (2) lists the dense star fields observed. Column (3) and Column (4) list the numbers of observations and filter used for dense star fields and Himalia, respectively. Column (5) shows which telescope was used.

Table 3 Phase Effect for Himalia with Respect to the Observation Time

Observation time (UTC) (1)	Distance (AU) (2)	Apparent diameter (3)	Phase angle (4)	V (with extinction) (5)	Phase effect (6)
2015–01–31 $15^{\rm h}\ 13^{\rm m}$	4.418	$0.1''$	$+1^\circ 19' 26''$	15.80	$0.0004''$
2015–02–13 $16^{\rm h}\ 01^{\rm m}$	4.416	$0.1''$	$+1^\circ 23' 12''$	15.77	$0.0005''$
2015–02–12 $15^{\rm h}\ 10^{\rm m}$	4.415	$0.1''$	$+1^\circ 10' 50''$	15.78	$0.0004''$
2015–02–14 $15^{\rm h}\ 53^{\rm m}$	4.418	$0.1''$	$+1^\circ 35' 06''$	15.77	$0.0005''$

Notes: Column (1) shows several typical observation times. Column (2) lists the distance of Himalia from the Earth. Column (3) and Column (4) list the apparent diameter and the phase angle, respectively. Column (5) shows the V magnitude with extinction. Column (6) lists the phase effect for Himalia.

Their standard deviations are $0.044''$ and $0.036''$ in each direction.

5 DISCUSSIONS

In order to check the precision of our CCD observations for Himalia, two different ephemerides were selected to calculate theoretical positions, and then comparisons were made with the observed ones. The first ephemeris, developed by the IMCCE, includes the satellites theory by Emelyanov (2005) and the planetary ephemeris INPOP13c (Fienga et al. 2014). The second ephemeris, which includes the satellite theory JUP300 (Jacobson 2013) and the planetary theory DE431 (Folkner et al. 2014), was developed by JPL.

Figure 3 shows the $(O-C)$ residuals of the topocentric apparent positions of Himalia in comparison with different ephemerides. An obvious systematic deviation between the

Table 4 Statistics on the $(O-C)$ Residuals of the Positions of Himalia before and after GD Corrections

Observation Date and Telescope (1)	GDC (2)	$\langle O-C \rangle$ RA (3)	SD (4)	$\langle O-C \rangle$ Dec (5)	SD (6)
2015–01–31	Before	0.021	0.072	–0.007	0.049
2.4 m	After	–0.009	0.013	0.009	0.018
2015–02–07	Before	–0.106	0.041	–0.092	0.065
2.4 m	After	–0.065	0.014	–0.023	0.018
2015–02–08	Before	–0.096	0.107	–0.087	0.083
2.4 m	After	–0.042	0.054	–0.052	0.062
2015–02–09	Before	–0.011	0.037	–0.062	0.051
2.4 m	After	–0.029	0.016	–0.006	0.018
2015–02–10	Before	–0.028	0.084	–0.083	0.054
2.4 m	After	–0.011	0.021	–0.009	0.024
2015–02–11	Before	–0.072	0.090	–0.035	0.046
2.4 m	After	–0.002	0.017	–0.009	0.019
2015–02–12	Before	–0.007	0.078	–0.002	0.087
2.4 m	After	0.005	0.010	0.018	0.022
2015–02–13	Before	0.023	0.097	0.009	0.089
2.4 m	After	0.054	0.012	0.046	0.017
2015–02–12	Before	0.002	0.047	–0.042	0.011
1 m	After	0.022	0.045	–0.019	0.012
2015–02–14	Before	0.034	0.029	0.017	0.035
1 m	After	0.045	0.031	0.009	0.035
Total	Before	–0.025	0.085	–0.038	0.072
	After	–0.004	0.044	–0.002	0.036

Notes: Column (1) shows the observational dates and the telescope. The second column indicates whether GD corrections are applied. The following columns list the mean of $(O-C)$ residuals and their standard deviation (SD) in right ascension and declination, respectively. All units are in arcsec.

Table 5 Statistics on $(O-C)$ Residuals for Himalia Compared to Corresponding Values from Different Ephemerides

N (1)	Ephemerides (2)	$\langle O-C \rangle$ RA (3)	SD (4)	$\langle O-C \rangle$ Dec (5)	SD (6)
185	Emelyanov (2005)/INPOP13c	–0.004	0.044	–0.002	0.036
	JUP300/DE431	0.098	0.045	–0.051	0.035

Notes: Column (1) shows the number of CCD observations. Column (2) indicates the different ephemerides used. The following columns list the mean of the $(O-C)$ residuals and its corresponding standard deviation in right ascension and declination. All units are in arcsec.

two ephemerides can be seen, but the dispersion for each night between the two ephemerides is similar.

Table 5 shows the statistics of $(O-C)$ residuals for Himalia after GD corrections for different ephemerides. The means of $(O-C)$ residuals after GD corrections for ephemerides calculated by IMCCE are $-0.004''$ and $-0.002''$ in right ascension and declination, respectively. The values of standard deviation in each direction are $0.044''$ and $0.036''$. For ephemerides computed by JPL, the means of $(O-C)$ residuals after GD corrections are $0.098''$ and $-0.051''$ in right ascension and declination, respectively. The values of standard deviation in each direction are $0.045''$ and $0.035''$. A good agreement can be seen for precision between both ephemerides. However, differences in the mean of $(O-C)$ residuals in right ascension and declination between two ephemeris can be found.

To compare our CCD observations with previous ones, some major observational statistics of Himalia retrieved from the Minor Planet Center (MPC) are listed. The ephemeris was developed by the IMCCE which includes

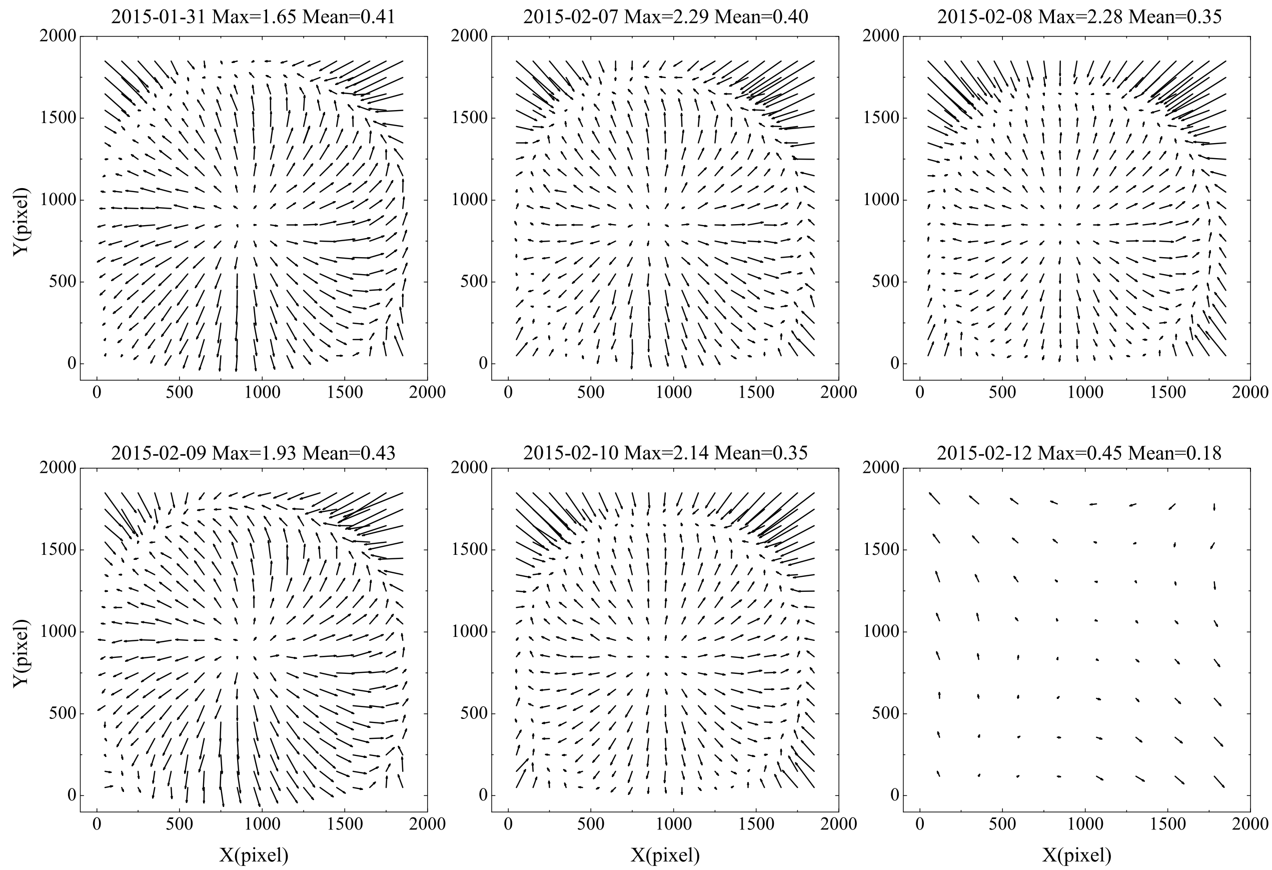

Fig. 1 GD patterns associated with the 2.4 m and 1 m telescopes administered by Yunnan Observatories. The first five panels show the GD patterns derived from CCD observations of NGC 1664 and NGC 2324 with the 2.4 m telescope. The rightmost panel in the bottom row shows the GD pattern derived from CCD observations of M35 with the 1 m telescope. All observations were made with the Johnson I filter. The observational dates, the maximum GD values and the mean GD values are listed on the top of each panel in units of pixels. A factor of 200 is used to exaggerate the magnitude of each GD vector.

the satellite theory by Emelyanov (2005) and the planetary ephemeris INPOP13c (Fienga et al. 2014).

Table 6 shows comparisons of the means of $(O - C)$ residuals and their standard deviations. The positions of Himalia are topocentric astrometric positions. It can be seen that our observations have comparable precision.

In Figures 2 and 3, we can see that the dispersion of positions for Himalia with the 2.4 m telescope during the third night is somewhat worse than other nights after GD corrections. We give an explanation that serious meteorological conditions happened on that night, and this would influence the positional measurements. It can also be seen that there is a systematic trend appearing in the values of $(O - C)$ in Figure 3, especially in right ascension. This may be caused by the existence of zonal errors in the star catalog. Another reason might come from the ephemeris. More observations are needed to confirm this in the future.

6 CONCLUSIONS

In this paper, we have made a preliminary analysis of CCD astrometric observations targeting Himalia. A total of 185 CCD observations were taken with the 2.4 m and 1 m telescopes administered by Yunnan Observatories. A series of error effects were analyzed, including GD, atmospheric refraction, and also the phase effect. The positional precision for Himalia has significantly improved after GD corrections. Comparisons with two different ephemerides have been made. The results have shown that the means of $(O - C)$ residuals of Himalia are $-0.004''$ and $-0.002''$ by using ephemerides developed by the IMCCE in right ascension and declination, respectively. The standard deviations are $0.044''$ and $0.036''$ in each corresponding direction.

In consideration of the fewer number of reference stars in each CCD frame of Himalia, the high-order plate model cannot be applied. In order to use the low-order plate model which is a plate model with four constants in this paper, the GD effects should be corrected accurately. Furthermore, the precision of a star catalog also directly influences the positional measurements of targets. In the near future, a new catalog developed by the ESA astrometry satellite Gaia (Lindegren et al. 2008) will be released since the Gaia probe was launched on 2013 December 19.

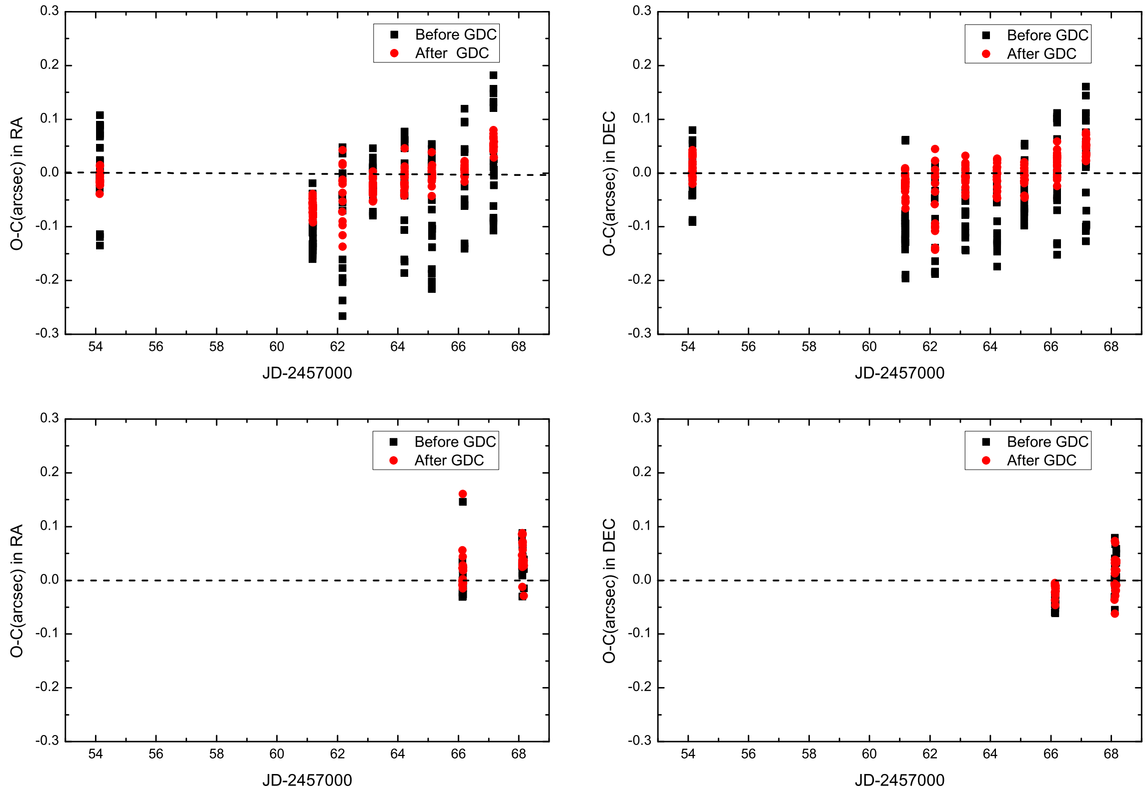

Fig. 2 $(O-C)$ residuals of the topocentric apparent positions of Himalia compared to the satellite theory by Emelyanov (2005), together with the planetary ephemeris INPOP13c, expressed in terms of Julian Dates. The *upper two panels* show the $(O-C)$ residuals for the CCD observations with the 2.4 m telescope, and the *lower two panels* show the $(O-C)$ residuals for the CCD observations with the 1 m telescope. The *dark points* represent the $(O-C)$ residuals before GD corrections and the *red ones* represent the $(O-C)$ residuals after GD corrections.

Table 6 Comparisons Made with other Observations Retrieved from the MPC

Observatory code	Frame no.	$\langle O-C\rangle$ RA	SD	$\langle O-C\rangle$ Dec	SD	Time (yr)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
689	68	–0.046	0.149	–0.006	0.131	2000–2001
689	106	0.005	0.148	–0.020	0.143	2001–2003
689	103	–0.001	0.182	–0.011	0.191	2003–2007
415	24	–0.007	0.106	0.071	0.088	2008
809	23	–0.048	0.092	0.019	0.047	2007–2009
511	357	–0.018	0.049	–0.011	0.061	1997–2008
874	238	–0.075	0.175	–0.007	0.034	1992–2014
874	560	0.005	0.069	–0.018	0.053	1992–2014
874	56	–0.036	0.113	–0.019	0.069	1992–2014
This paper	185	–0.004	0.044	–0.002	0.036	2015

Notes: Column (1) shows the IAU code of observatories relevant to this study. Column (2) lists the number of CCD observations. The following columns give the mean of the $(O-C)$ residuals and their associated standard deviation (SD) in right ascension and declination. All of the positions of Himalia are topocentric astrometric positions. All units are in arcsec.

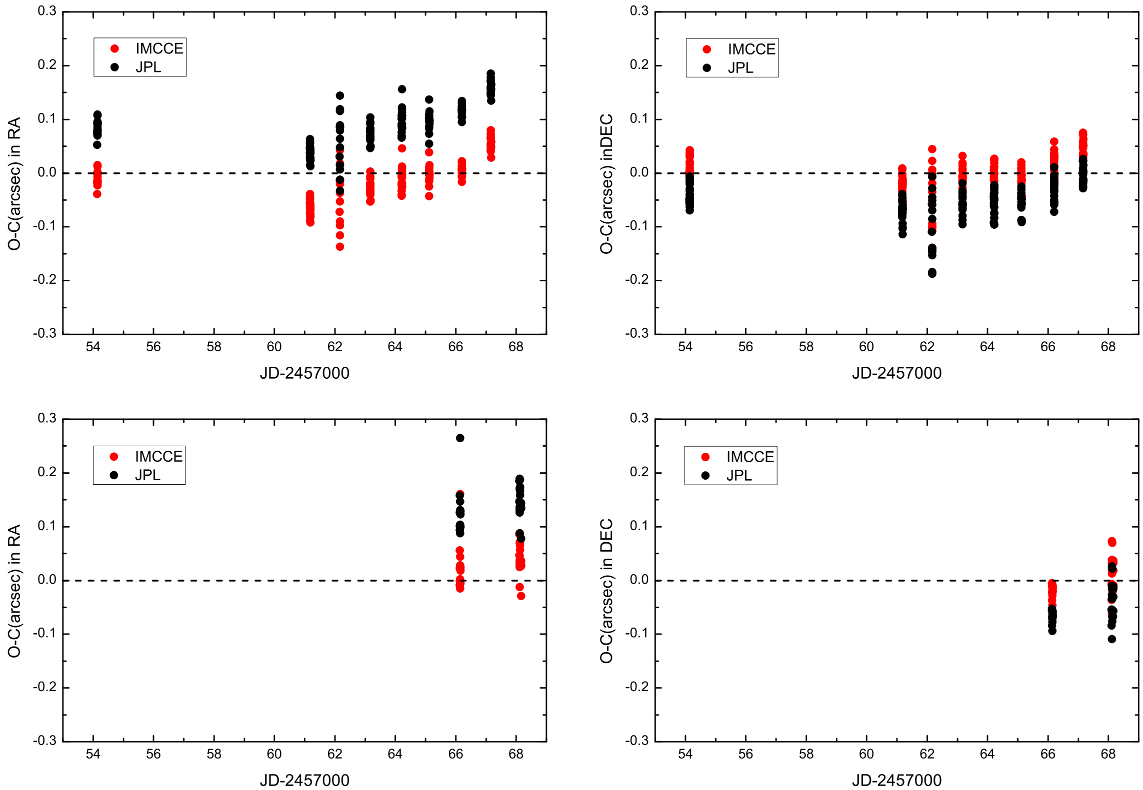

Fig. 3 $(O-C)$ residuals of the topocentric apparent positions of Himalia compared to two ephemerides. The *red points* represent the $(O-C)$ residuals after GD corrections for the ephemeris developed by the IMCCE which includes satellite theory by Emelyanov (2005) and planetary ephemeris INPOP13c. The *dark points* represent the $(O-C)$ residuals after GD corrections for the ephemeris developed by JPL which includes satellite theory JUP300 and planetary theory DE431. The *upper two panels* show the $(O-C)$ residuals for the CCD observations with the 2.4 m telescope, and the *lower two panels* show the $(O-C)$ residuals for the CCD observations with the 1 m telescope.

Precise star positions to be derived by the new catalog will render better predictions with the only source of error being the ephemerides (de Bruijne 2012; Gomes-Júnior et al. 2015). We believe that higher astrometric precision in the positions of irregular satellites will be achieved.

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