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CCD astrometric observations of the five major Uranian satellites made in 1998–2007 and comparison with theory[★]

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ABSTRACT

An observational campaign of the five Uranian major satellites was carried out during the period 1998–2007. A total of 2358 satellite observations in 1025 CCD frames were taken at two observational stations near Beijing and Shanghai with two telescopes of 0.8 and 1.56 m diameter. The observed positions were compared to the two Uranian satellites' recent ephemerides GUST06 and LA06. The result of this comparison has shown that the accuracy of our observations is about 100 mas for all the satellites. The satellite theories GUST06 and LA06 appear to be quite reliable for the first four satellites, with an accuracy of about 50 mas, but for Miranda the accuracy is only about 200 mas. Moreover, we have found a systematic error between the two planetary ephemerides DE405 and DE421 of about 80 mas for the period of our observations.

Key words: astrometry – planets and satellites: general.

1 INTRODUCTION

Before 2000, except our group, several other groups of regular observations of the five Uranian major satellites were carried out by different authors such as Veiga & Vieira Martins (1994, 1995, 1999), Stone (2001) and Veiga, Vieira Martins & Andrei Alexandre (2003). In recent years, the focus on the Uranian system was above all concentrated on mutual events by the scientific community so that the regular observation of the five major Uranian satellites was a little neglected. Consequently, the Natural Satellite Data Base (NSDB) of the Institut de Mécanique Céleste et de Calcul des Ephémérides shows that only a few data were observed in the most recent years by Veiga & Bourget (2006), Izmailov et al. (2007) and Khovritchev (2009).

Observing Uranian satellites is a part of the whole CCD observational campaign that we have run from 1994 for Saturnian satellites (Qiao et al. 1999) and from 1995 for Uranian satellites (Shen et al. 2002). We have continued this observational campaign with the Saturnian satellite Phoebe (Qiao et al. 2006, 2011) and the two Neptunian satellites Triton (Qiao et al. 2007) and Nereid (Qiao et al. 2008). For Uranian satellites, our previous work (Shen et al.

2002) presented a total of 864 satellite observations obtained in the period 1995–1997. In this paper, we publish the observed positions of the five major Uranian satellites obtained during the following period spanning from 1998 to 2007.

A comparison of the satellites' observed positions with ephemerides was carried out to evaluate the precision of our observations. The Uranian satellites' ephemerides that we used here were generated from the two major recent theories named GUST06 and LA06. Simultaneously, the two planetary ephemerides DE405 and DE421 were used with the two different satellite ephemerides. The so-obtained [observed minus calculated (O – C)] residuals will also be used to detect a possible systematic difference between the two planetary ephemerides DE405 and DE421.

2 OBSERVATION AND MEASUREMENT

2.1 Observation

All along the period 1998–2007, we observed the five major satellites of Uranus during a total of 33 nights. These five satellites are very faint, with magnitudes between 13.8 for Titania and 16.5 for Miranda and their orbits are rather near their primary. Their orbital period is from about 1.5 d for Miranda to about 13.5 d for Oberon. Some detailed physical characteristics of the first five Uranian satellites are presented in Table 1.

Two different telescopes were used to observe the Uranian satellites during this campaign: the 1.56 m astrometric reflector

[★]The data are available in electronic form by E-mail, as Supplementary Material to the online version of the paper, at the CDS via anonymous FTP to cdsarc.u-strasbg.fr or via <http://cdsweb.u-strasbg.fr/Abstract.html>.

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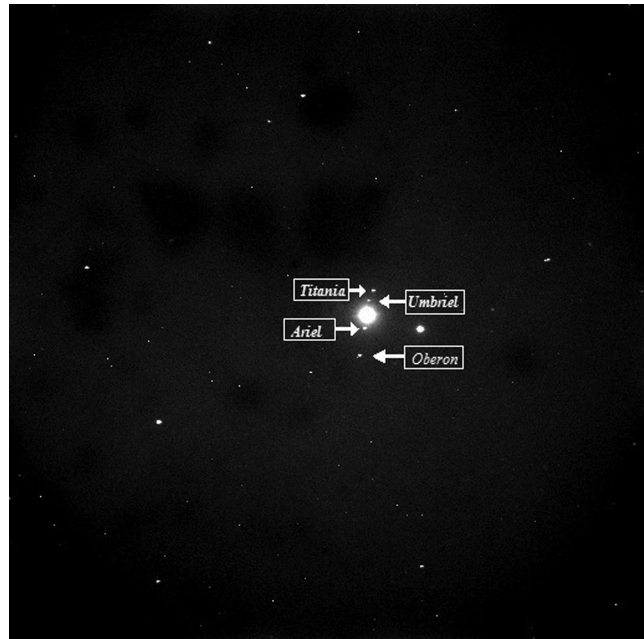
Table 1. Visual magnitude at opposition, semimajor axis and orbital period for the first five Uranian satellites.

Satellites	M_v	Semimajor axis ($\times 10^3$ km)	Orbital period (d)
Miranda	16.5	130	1.41
Ariel	14.4	191	2.52
Umbriel	14.8	266	4.14
Titania	13.8	436	8.71
Oberon	14.2	584	13.46

at the Sheshan station of the Shanghai Astronomical Observatory (121°184E, 31°096N, H97m) near Shanghai, and the 0.80 m astrometric reflector at the Xinglong station of the National Astronomical Observatory (117°577E, 40°396N, H940m) near Beijing. The 1.56-m telescope, initially equipped with a CCD chip of 1024×1024 pixel for the first observations made in 1998, was equipped with a wider CCD chip of 2048×2048 pixel since 2002. The dimension of the new field was increased nearly by a factor of 3 (11.2×10.8 arcmin²) with respect to the field of the initial CCD chip (4.3×4.3 arcmin²), so that the area of the new field was increased nearly by a factor of 7. The 0.80-m telescope was equipped with a 1340×1300 pixel CCD chip corresponding to a field of about 11.4×11.1 arcmin². Both telescopes were equipped with cooled CCD cameras. More information about the telescopes and their CCD cameras is listed in Table 2.

For all observations, the exposure time was from 14 to 120 s, depending on the local weather conditions, elevation above the horizon and on the setting of the different telescopes. No filter was used during the observations. The flat-field images were taken at dusk and dawn. The bias was taken at the beginning and at the end of the observation. The dark field images were taken at the end of every day of observation. The saturation level of the images is set in 65 536 ADU in measurement software. The image of the planet is often saturated and the signal-to-noise ratio of the light flux can reach about 100 for the satellites and some hundreds for the stars. The full width at half-maximum is from about 3 to 9 pixel in the Sheshan station and from about 3 to 6 pixel in the Xinglong station. A typical raw CCD image of major Uranian satellites is displayed in Fig. 1.

There were eight different observational series for the five oppositions of Uranus in 1998, 2002, 2003, 2006 and 2007, as presented in Table 3. Nearly all the observations were made with the 1.56 m astrometric reflector at the Sheshan station. The only observations made with the 0.80-m reflector at the Xinglong station were per-

**Figure 1.** A typical raw CCD image of Uranian major satellites taken on 2006 September 20 at the Sheshan station with 1.56-m telescope equipped with the 11.2×10.8 arcmin² field CCD chip.

formed during the observational series no. 5 running from 2006 August 29 to 30.

2.2 Measurement

As mentioned in our previous similar works (Qiao et al. 2008, 2011), we have used the powerful *ASTROMETRICA* software to measure the CCD digital images. This is an interactive software tool for scientific grade astrometric data reduction of CCD images. The detailed procedure of measurement with *ASTROMETRICA* has been previously described by Qiao et al. (2008) to which the interested reader can refer for more information.

As most of our observations of Uranian satellites were taken in 2006 and 2007, they have been made in a period favourable to mutual events of the Uranian system which occurred, as they do every 42 years, in the period 2006–2009. During this special period favourable to mutual events, two satellites have a higher probability to present a very close approach than during a classical period. In these conditions, we had to eliminate a significant number of satellite measurements, as their images could not be distinguished from the images of another satellite. However, we finally succeeded in

Table 2. Specifications of the two telescopes and CCD chips used for the observations of the five major satellites of Uranus. Telescope A refers to the 1.56-m reflector equipped with the initial CCD chip in 1998. Telescope B refers to the 1.56-m reflector equipped with a wider CCD chip since 2002 and Telescope C refers to the 0.8-m telescope.

Telescope	A	B	C
Diameter of primary mirror (cm)	156	156	80
Focal length (mm)	15 600	15 600	8000
Size of CCD array (pixel)	1024×1024	2048×2048	1340×1300
Size of pixel (μm)	19	24	20
Pixel size (arcsec ²)	0.25×0.25	0.32×0.32	0.51×0.51
Field of view (arcmin ²)	4.3×4.3	11.2×10.8	11.4×11.1

Table 3. A statistics of our observations of the five major Uranian satellites for the eight different observational series covering the five oppositions of Uranus in 1998, 2002, 2003, 2006 and 2007. The number of observations are given for each satellite and for each night of observation. N is the total number of observations and N_n is the total number of nights of observations for each satellite. N_d is the number of satellite observations for each series. The mean residuals $(O - C)\mu$ and standard deviations to the mean σ are given in right ascension and declination, computed with the combination of DE421 and GUST06. They are expressed in arcseconds. The used telescope is characterized by the letter A, B or C as defined in Table 2.

Series	Day (y m d)	Ariel	Umbriel	Titania	Oberon	Miranda	N_d	μ_α (arcsec)	μ_δ (arcsec)	σ_α (arcsec)	σ_δ (arcsec)	Telescope
1	1998 11 07	2	1	2	3							
	1998 11 10	10	10	10	10	5	53	-0.01	-0.01	0.10	0.08	A
2	2002 09 03	13	7	13	21		54	0.01	-0.06	0.12	0.09	B
	2003 08 21		2	13	13							
3	2003 08 22	6	2	4	7		70	0.01	-0.07	0.09	0.09	B
	2003 08 23	4	5	7	7							
4	2006 08 20			25	25							
	2006 08 22			24	25							
	2006 08 23			21	26		340	-0.04	-0.04	0.06	0.08	B
	2006 08 24	4	30	33	36							
5	2006 08 25		25	30	30	6						
	2006 08 29			7	8		83	-0.04	0.00	0.10	0.10	C
6	2006 08 30		13	22	33							
	2006 09 18				38	9						
	2006 09 19			11	12							
	2006 09 20	22	21	22	22							
	2006 09 21	10	3	26	26							
	2006 09 22		26	28	29		639	0.01	-0.01	0.08	0.08	B
	2006 09 23		5		14							
	2006 09 25	33		39	39							
7	2006 09 26	18	27	27	29							
	2006 09 27			50	53							
	2007 08 11	17	16		19							
	2007 08 13		18	24			308	-0.06	0.01	0.08	0.11	B
8	2007 08 15	24	24	17	24							
	2007 08 16	46		46	33							
	2007 09 09	28	42	30	11							
	2007 09 10			6	3							
	2007 09 11		67		88							
	2007 09 12	42		57	84		811	-0.02	0.08	0.08	0.10	B
Nn	2007 09 13	25	23	43	43							
	2007 09 15		49									
N	2007 09 16			85	85							
		16	21	28	31	3						
		304	416	722	896	20	2358					

obtaining a total of 2358 satellite observations from 1025 available CCD frames. For each of the five observed satellites, the total number of observations was 304 for Ariel, 416 for Umbriel, 722 for Titania, 896 for Oberon and only 20 for Miranda, due to its faintness and proximity to the primary. Among the total of 33 nights of observation spreading over the eight observational series from 1998 to 2007, the respective number of nights during which we have obtained available satellite observations were 16 for Ariel, 21 for Umbriel, 28 for Titania, 31 for Oberon and three for Miranda. A detailed information about the distribution of our observations is given in Table 3 which also presents residuals computed for each observational series.

3 ASTROMETRIC REDUCTION AND RESULTS

In our previous research relating Uranian satellites' observed positions (Shen et al. 2002), we used the 'brighter moon calibration'

method to reduce the astrometric positions of satellites. Although this method may introduce some systematic errors in the derived observed positions of satellites (Shen et al. 2001), we used it because there was a lack of reference stars in each CCD frame to allow us to use a classical astrometric reduction.

Fortunately, in the present work, as in our latest works (Qiao et al. 2006, 2007, 2008, 2011), we have been able to carry out a classical astrometric reduction, thanks to a couple of different factors. First of all, the CCD field of our camera was improved to be wider, and then, high-density star catalogues such as UCAC2 (Zacharias et al. 2004) had become available. In this work, we have chosen the UCAC2 reference star catalogue due to its very high density, with positions and proper motions of more than 48 million stars given at the epoch J2000.0 on the ICRS, combined with a very good accuracy between 15 and 70 mas, depending on the magnitude from 9 to 16, and an absence of significant local errors, lower than 10 mas.

Table 4. An extract from the list of the observed positions of the first five Uranian satellites. U1, U2, U3, U4 and U5, respectively, represent Ariel, Umbriel, Titania, Oberon and Miranda. The decimal day corresponds to the mean time of each exposure. Right ascension and declination are topocentric and are referred to the mean equator and equinox of J2000.0. Sat. is the number of satellite. Y, M and D, respectively, represent the year, month and day. Site is the observing site. The full version of the table is available online.

Sat.	Y	M	D (UTC)	α (h m s)	δ ($^{\circ}$ ' ")	Site
...
U1	1998	11	10.428 125	20 46 37.747	-18 37 18.95	337
U1	1998	11	10.463 368	20 46 37.902	-18 37 17.13	337
...
U2	1998	11	10.428 125	20 46 37.539	-18 37 20.05	337
U2	1998	11	10.463 368	20 46 37.680	-18 37 18.34	337
...
U3	1998	11	10.428 125	20 46 37.855	-18 37 45.81	337
U3	1998	11	10.463 368	20 46 37.983	-18 37 44.78	337
...
U4	1998	11	10.428 125	20 46 36.700	-18 37 31.01	337
U4	1998	11	10.463 368	20 46 36.840	-18 37 29.66	337
...
U5	1998	11	10.428 125	20 46 38.445	-18 37 27.42	337
U5	1998	11	10.463 368	20 46 38.532	-18 37 26.94	337
...

Generally, there are between 6 and 15 UCAC2 reference stars available in our images. There is an exception for the observational series no. 1 (opposition 1998) with only from three to five UCAC2 stars, due to the small field of the used telescope A then equipped with the small CCD chip (Table 2). Moreover, the weather condition is a factor which can affect the number of available reference stars on each frame. Nevertheless, we always had enough reference stars to allow us to use a classical astrometric reduction method. According to the number of reference stars, we have chosen either a linear fit or a quadratic fit for the plate constants determination.

In Table 4, we present an extract from the list of the observed positions of Uranian satellites determined here. These data are

topocentric and the reference system is defined by the mean equator and equinox J2000.0 in the ICRF. The complete data can be obtained on the web site of the CDS at the following address: <http://cdsweb.u-strasbg.fr/Abstract.html>, or via anonymous FTP to cdsarc.u-strasbg.fr.

4 COMPARISON WITH THEORETICAL POSITIONS

We have compared our observations to two different kinds of ephemerides: analytical and numerical integration. The first ephemeris, named GUST06, is an improved version of the initial analytical ephemeris GUST86 (Laskar & Jacobson 1987), which has been fitted to a larger span of observations from 1911 to 2005 (Arlot & Sicardy 2008). The second ephemeris is the recent numerical integration LA06, initially established by Lainey (2008) for predicting the mutual events of Uranian satellites (Arlot, Lainey & Thuillot 2006). LA06 was fitted to observations from 1948 to 2005. Both of these theories, GUST06 and LA06, have been adjusted to about the same time span of observations of Uranian satellites and are available on the IMCCE web site which also proposes different planetary ephemerides. On this web site, Uranian satellites' positions from GUST06 can be obtained for the whole period of our observations (1998–2007), so that all our observations can be compared to this theory. In contrast, as LA06 was especially developed for predicting the mutual events campaign of Uranian satellites occurring in the period 2006–2009, it is only available for a period which begins from 2006 January 1. Consequently, the 177 observations of the Uranian satellites that we had made before 2006 cannot be compared to LA06. However, all the other 2181 observations, made since 2006 January 1 corresponding to 93 per cent of the total of the 2358 observations presented here, have been compared to LA06.

Simultaneously, we have chosen the two planetary ephemerides DE405 and DE421 to combine them with the two different satellites' ephemerides GUST06 and LA06. In our previous work (Shen et al. 2002), we had already used DE405 (Standish 1998)

Table 5. Values of mean residuals $(O - C)\mu$ and standard deviations to the mean σ of our observations, expressed in arcseconds. Residuals are given for each satellite and from the comparison of our observations to the positions derived from the two different satellite ephemerides GUST06 and LA06 and from the two different planetary ephemerides DE421 and DE405. All residuals are computed for the period 2006–2007, commonly available for both theories LA06 and GUST06, which include 93 per cent of all our observations.

Satellite ephemeris	Planetary ephemeris	(O - C)	Ariel	Umbriel	Titania	Oberon	Miranda
LA06	DE421	μ_{α}	-0.03	-0.02	-0.01	-0.02	-0.08
		μ_{δ}	0.00	0.04	0.00	0.02	0.31
		σ_{α}	0.09	0.09	0.08	0.08	0.10
		σ_{δ}	0.13	0.12	0.09	0.09	0.09
		μ_{α}	-0.11	-0.10	-0.10	-0.10	-0.16
		μ_{δ}	-0.08	-0.04	-0.08	-0.07	0.23
	DE405	σ_{α}	0.09	0.09	0.08	0.08	0.10
		σ_{δ}	0.13	0.11	0.09	0.09	0.09
		μ_{α}	-0.02	-0.02	-0.02	-0.02	-0.06
		μ_{δ}	0.00	0.04	0.02	0.03	0.31
		σ_{α}	0.08	0.09	0.08	0.08	0.10
		σ_{δ}	0.13	0.12	0.09	0.09	0.08
GUST06	DE421	μ_{α}	-0.11	-0.10	-0.10	-0.11	-0.15
		μ_{δ}	-0.09	-0.04	-0.07	-0.06	0.23
		σ_{α}	0.08	0.09	0.08	0.08	0.10
		σ_{δ}	0.13	0.12	0.09	0.09	0.09

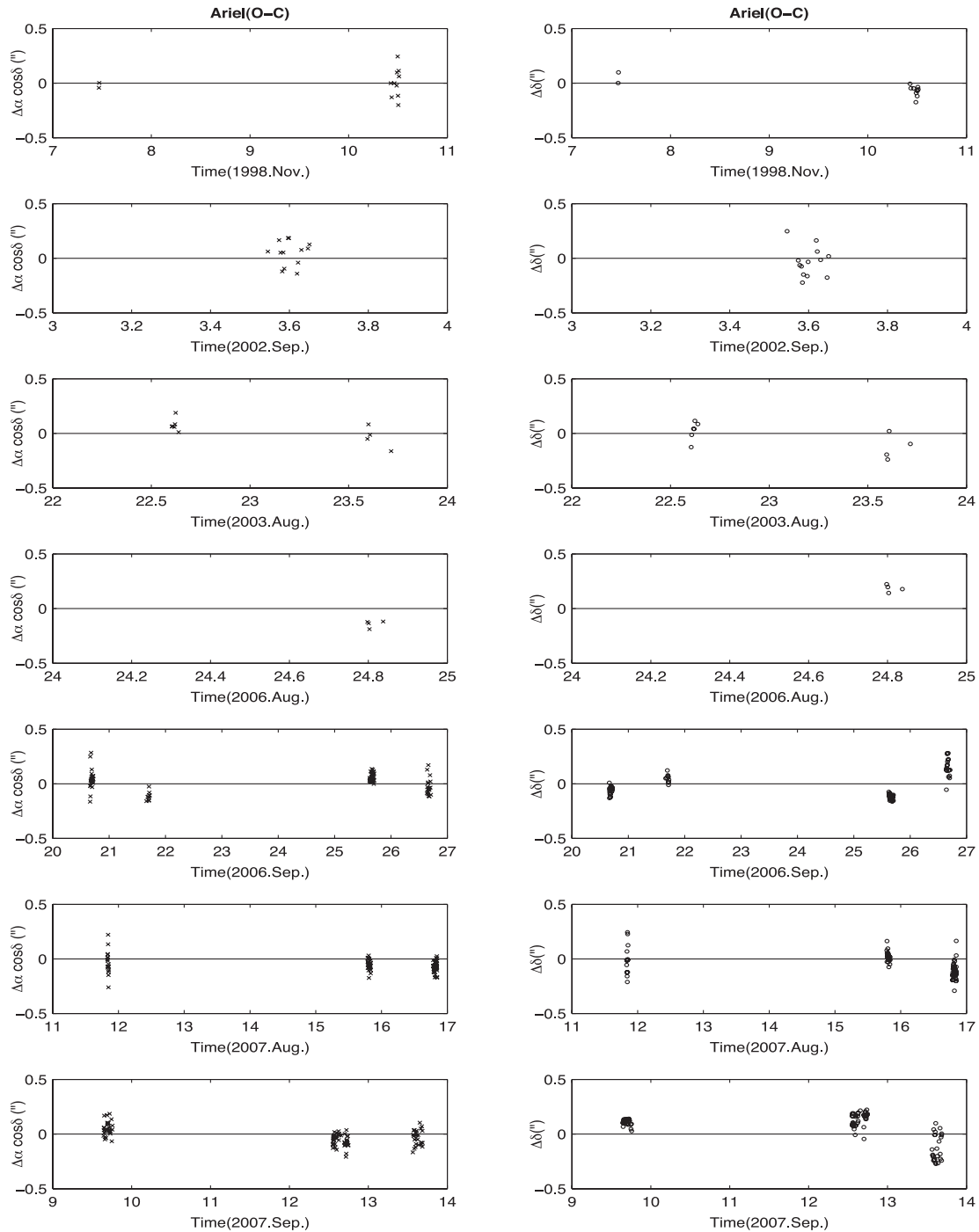


Figure 2. Residuals (O – C) versus time of Ariel in right ascension and declination for the seven successive periods of observation from 1998 to 2007. Residuals are computed from the comparison of our observations to the ephemerides DE421 for Uranus and GUST06 for satellites.

which is an improvement of DE403. DE405 is fitted to several kinds of observations, derived from meridian circles, astrolabes, CCD frames and occultation rings of Uranus, obtained from 1911 to 1996.

DE421 is the latest planetary ephemeris developed at JPL by Folkner, Williams & Boggs (2009). For Uranus, DE421 was fitted to observations spreading over the period 1914–2007, significantly longer than that of DE405, mainly for recent years. Therefore, DE421 presents the real advantage to fit to observations made during the same period as our observations (1998–2007), while DE405

does not because it was fitted to observations made only before 1996.

Now, we analyse the residuals given in Table 3 computed from the theories GUST06 and DE421 for each observational series. The standard errors appear to be rather satisfactory with values between 50 and 100 mas for all the series in both coordinates. Moreover, the analysis of standard errors shows that the observations of the series no. 1, made in 1998 with the telescope A equipped with the small CCD chip, present a similar high quality as the other observations made with telescopes B and C equipped with wider CCD chips.

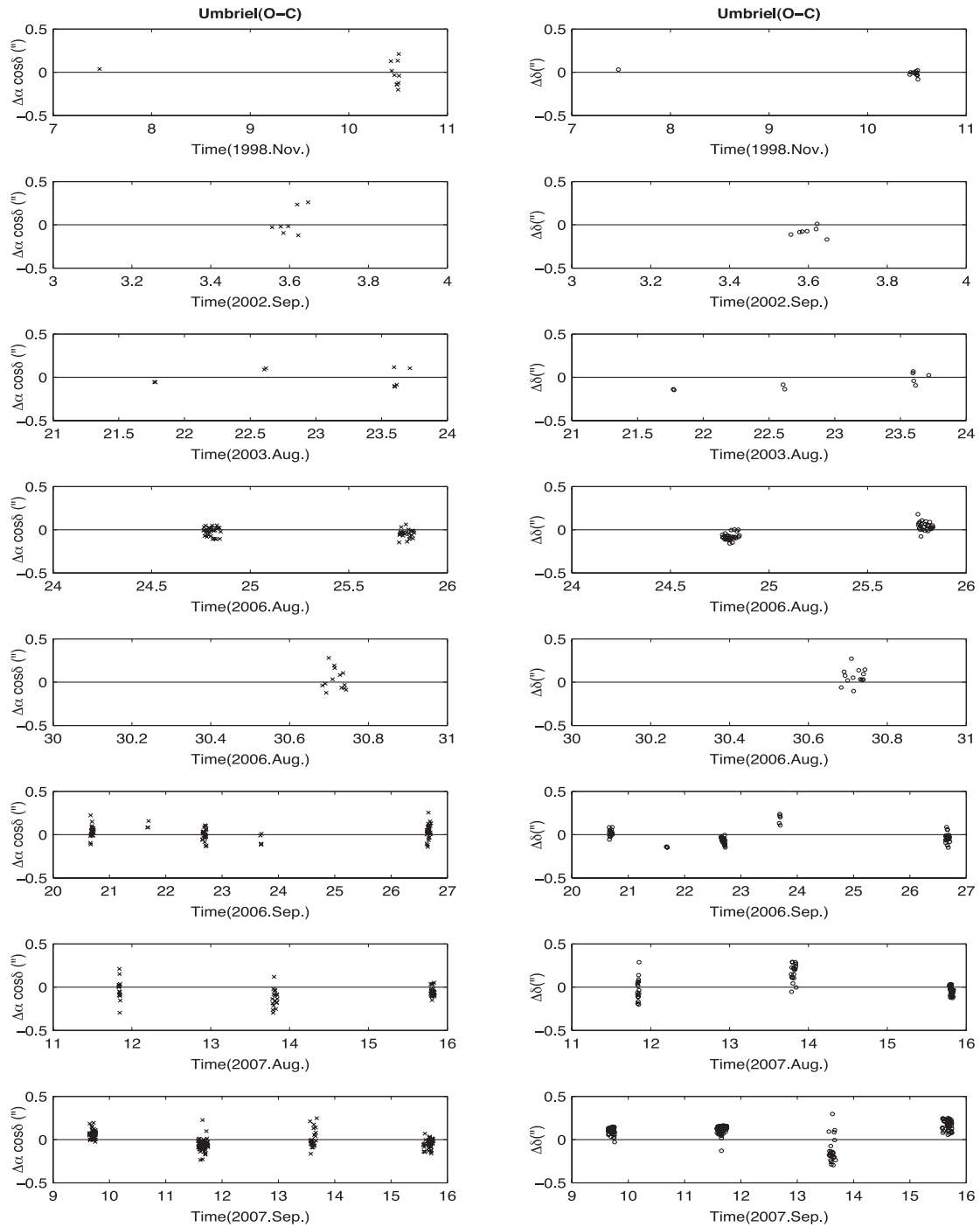


Figure 3. Residuals (O – C) versus time of Umbriel in right ascension and declination for the eight successive periods of observation from 1998 to 2007. Residuals are computed from the comparison of our observations to the ephemerides DE421 for Uranus and GUST06 for satellites.

In addition, the observations of the series no. 5, made with the 0.80-m telescope, also present a similar quality to that of all the other observations which have been made with the larger 1.56-m telescope. Moreover, the observations of the series no. 4, made in 2006 August with the telescope B, appear to be the most accurate as they present the lowest values of standard errors, between 50 and 80 mas. The mean residuals given in Table 3 show the following features. They present rather low values, lower than 100 mas, for all the series in both coordinates. Some series especially present very low mean residuals, under 10 mas, as the series no. 1 made in 1998

with telescope A and the series no. 6 made in 2006 with telescope B. This analysis shows, on the one hand, the very high quality of our observations and, on the other hand, the same high quality of the theories that we have used to compare our observations: GUST06 for the satellites and DE421 for Uranus. We shall analyse in more detail the accuracy of these different theories further in this work.

The two different planetary ephemerides combined with the two different satellites’ ephemerides presented above created four kinds of theoretical positions. The comparison of our observations to all

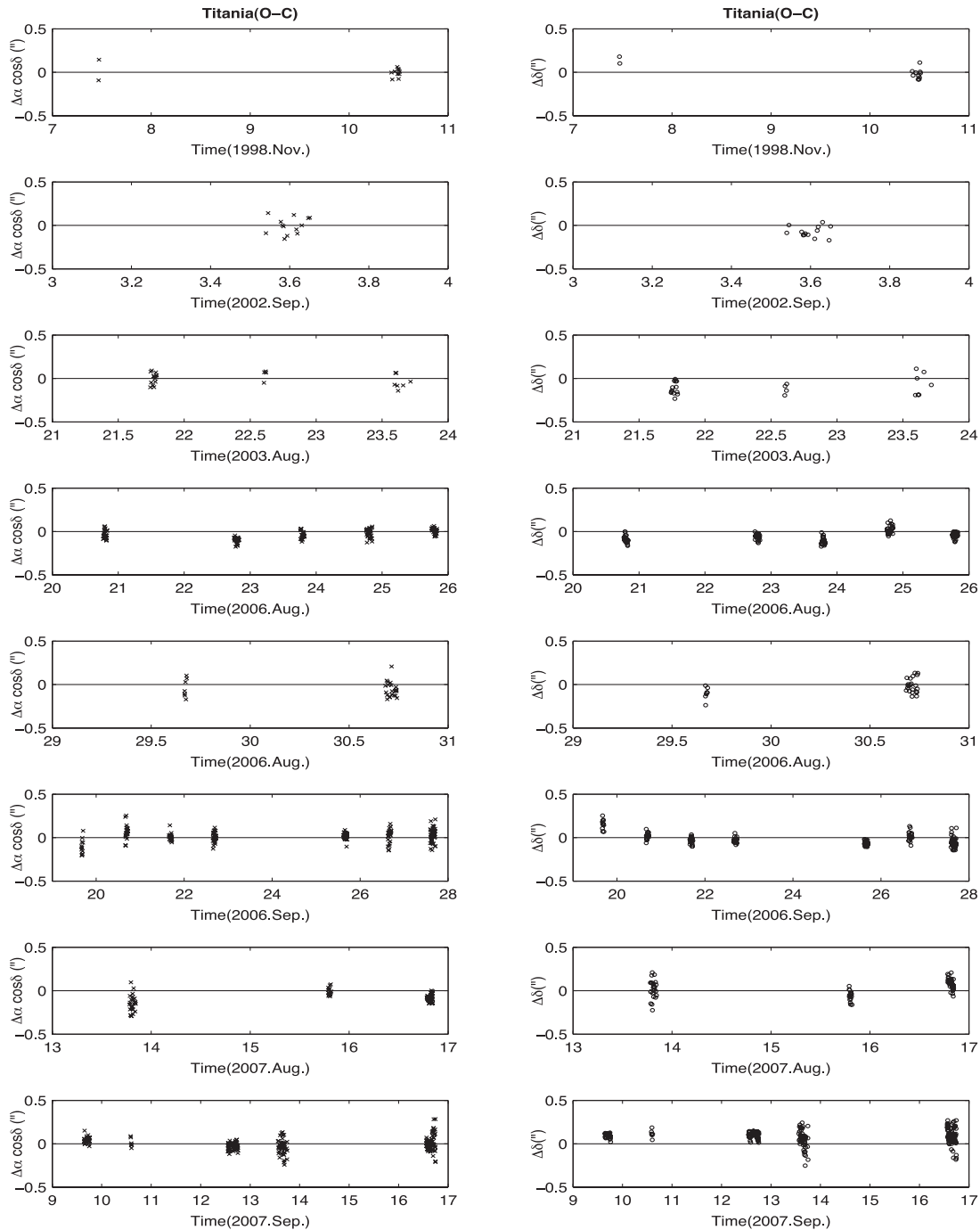


Figure 4. Residuals (O – C) versus time of Titania in right ascension and declination for the eight successive periods of observation from 1998 to 2007. Residuals are computed from the comparison of our observations to the ephemerides DE421 for Uranus and GUST06 for satellites.

these theoretical positions led to four groups of (O – C) values. The so-obtained mean residuals and standard deviations to the mean of (O – C) residuals of our observations are given in Table 5 presenting the values computed for the period 2006–2007 during which both of the two theories LA06 and GUST06 are available together. The values of residuals for all the period of our observations (1998–2007) have also been computed, for GUST06 only because LA06 is not available for the period before 2006. These values are very close, generally within less than 5 mas, to those obtained for the

period 2006–2007 given in Table 5. Here, we have not presented the values of residuals computed for all the period of our observations as they are not quite well adapted for an exact comparison of the theories and also because a large part of almost 93 per cent of our observations are already included in the period 2006–2007 of the residuals given in Table 5.

Moreover, the residuals (O – C) computed from GUST06 and DE421 are plotted versus time in Figs 2–6 for each of the five satellites. We can see that all the residuals, for each individual night

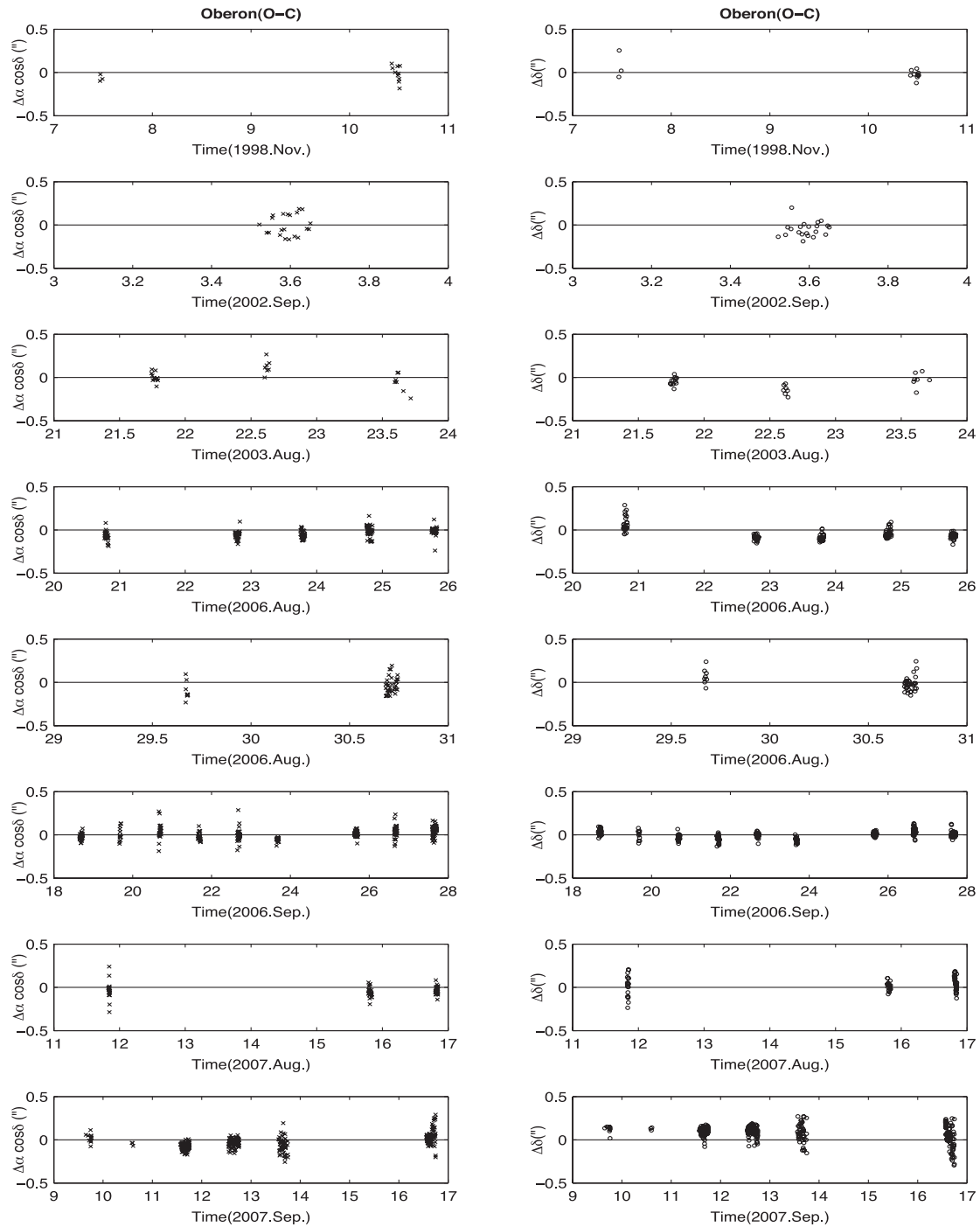


Figure 5. Residuals (O – C) versus time of Oberon in right ascension and declination for the eight successive periods of observation from 1998 to 2007. Residuals are computed from the comparison of our observations to the ephemerides DE421 for Uranus and GUST06 for satellites.

of observations, generally are lower than 200 mas, except in some rare cases, as for the observations of Miranda in 2006, which could be explained by rather bad weather conditions.

The analysis of the values of standard deviations listed in Table 5 shows that they are very close to 100 mas for all satellites and for both coordinates. They are slightly lower in right ascension than in declination. Therefore, we can evaluate the accuracy of our observations to about 100 mas, which is a rather good value for so faint satellites with their respective images often very close to that of another satellite and located near the much brighter primary.

Moreover, the mean residuals of Table 5 show that the positions derived from the two satellite ephemerides GUST06 and LA06 are very similar, generally with less than 5 mas of consistency in both coordinates for all satellites. There are some rare exceptions for which the consistency can reach nearly 15 mas in declination for Titania and Oberon and in right ascension for Miranda. This shows the very good consistency of the two satellite ephemerides.

Moreover, Table 5 shows that the mean residuals computed with the more recent planetary ephemeris DE421 for the period 2006–2007 generally are between the low values of 10 and 30 mas for

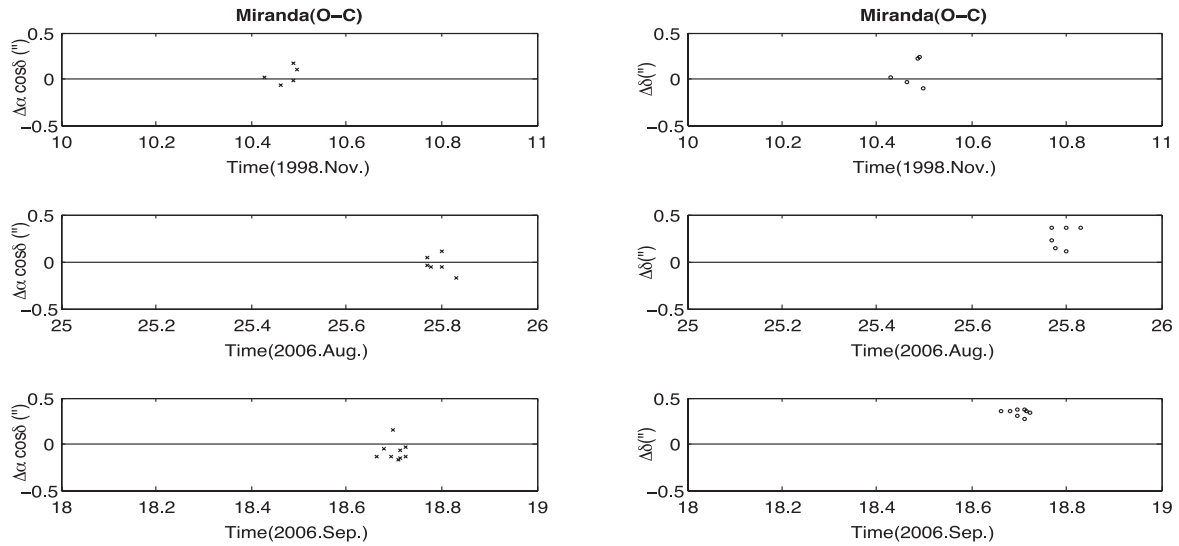


Figure 6. Residuals (O – C) versus time of Miranda in right ascension and declination for the three successive periods of observation from 1998 to 2007. Residuals are computed from the comparison of our observations to the ephemerides DE421 for Uranus and GUST06 for satellites.

all the satellites and for both coordinates, except in declination for Umbriel, with about 40 mas, and for Miranda, with values which can reach more than 70 mas in right ascension and 300 mas in declination. Consequently, the orbits of the first four Uranian satellites appear to be very accurately known, with an accuracy better than 50 mas in both coordinates. For the fifth smallest satellite Miranda, this accuracy is not so good and can reach about 200 mas.

Now, we must mention that the satellite residuals can be affected by possible errors of the planetary theories that we have used. To this aim, an analysis of the mean residuals of Table 5, whatever be the used satellite theory i.e. LA06 or GUST06, emphasizes a systematic difference between the two planetary ephemerides DE405 minus DE421 of about +80 mas in right ascension as well as in declination. In order to better analyse this systematic difference between both planetary ephemerides, we have downloaded the ephemerides of Uranus with DE405 and DE421 separately from 1992 January 1 to 2012 December 31. The values of DE405 minus DE421 were computed in right ascension and declination and are visualized versus time in Fig. 7. We can see that the evolution of the systematic difference between the two planetary ephemerides is increasing with time in both coordinates. For the epoch of our observations, Fig. 7 shows that the systematic difference is in quite good agreement with the value of about +80 mas for both coordinates derived just above from the analysis of the residuals given in Table 5.

5 CONCLUSION

We have presented here the results of our astrometric CCD observations of the first five Uranian satellites taken in eight different observational series covering the five successive oppositions of Uranus in 1998, 2002, 2003, 2006 and 2007. As the epoch of our observations was close to that of mutual events, the images of some satellites were often near the images of other satellites and then rather difficult to distinguish. However, we succeeded in obtaining 2358 satellite observations. We have compared our observations in using the two satellite ephemerides GUST06 and LA06 combined with the two planetary ephemerides DE421 and DE405. This comparison has shown the high accuracy of our observations, which is about

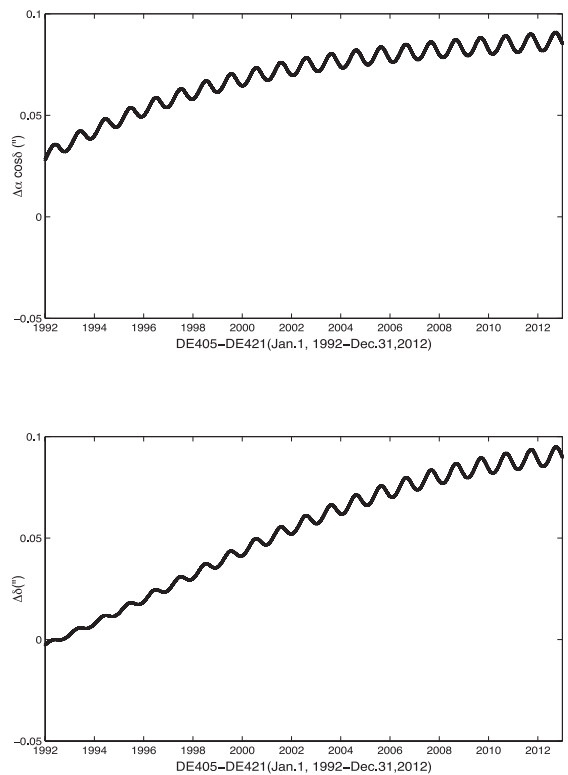


Figure 7. Differences versus time from 1992 to 2012 between planetary ephemerides DE405 minus DE421 for Uranus in right ascension and declination, expressed in arcseconds.

100 mas for all the satellites. This is a rather good result for so faint satellites with images often very close to the primary. Moreover, the analyses of the residuals have shown a very good consistency between the two satellite theories LA06 and GUST06, generally better than 50 mas, except for Miranda, with about 200 mas. In addition, we have detected a systematic difference between the two planetary ephemerides DE405 and DE421 for the Uranian system.

This difference reaches about 80 mas, both in right ascension and declination at the epoch of our observations, and is increasing with time.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 4. The list of the observed positions of the first five Uranian satellites. (<http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/sts240/-/DC1>).

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