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# Photometric and astrometric analysis of a mutual event between the Uranian satellites Miranda and Oberon

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Observations of the predicted occultation between the satellites Miranda and Oberon were performed on 2007 July 30. Data analysis reveals that the predicted magnitude drop for this phenomenon was overestimated and we establish an upper limit of $0\overset{m}{.}05$ for the phenomenon, perhaps due to a non-lambertian limb scattering. The new astrometry obtained from this run is in good agreement with the LA06 numerical model and these new data will improve the dynamical models of the Uranus system. The paper concludes with an uncertainty analysis on the parameters for the event, determined by the uncertainty of the magnitude drop of about 0.04 mag, and the difficulty to observe mutual phenomena between satellites in the Uranian system.



## 1 The Uranian system of satellites and the Uranus equinox

The equinox of the planet Uranus (defined when the sun crosses the planet's equator) is a once per 42 year event. The obliquity angle of Uranus is of $97\overset{\circ}{.}77$, and its retrograde rotation of 17.24 hours is more akin to a *rolling of the planet on its orbital plane*. Its sidereal period is estimated to be 84.01 years.

For Earth-bound astronomers the equinox provides a rare but critical opportunity for an edge-on view of the orbital planes of the principal satellites. For about 10 months around this nodal crossing, the satellites occult or eclipse one another when two of them are aligned with the Earth and the Sun, respectively. Modern astronomical instrumentation provides the first opportunity to make observations of these Uranian satellite mutual events.

As there is no mission currently scheduled to return to Uranus, the observations of the mutual events provide a prime opportunity for continuing our study of the dynamics of the satellite system. Here we describe observational results from our Uranian satellite mutual event measurements obtained in July 2007, at the beginning of the current mutual event season. These results provide important informations for the additional mutual events to follow.

First analysis of a Uranian mutual event, involving Umbriel and Oberon satellites, is already described by Hidas et al. (2008). The authors found a close agreement with the LA06 predictions (Arlot et al. 2006) and computed an impact parameter of $500 \pm 80$ km, slightly lower than the predicted one.

The study of mutual events of giant planet systems was initiated in the seventies (Arlot 1973; Arlot et al. 1974; Aksnes 1974). Several international campaigns were previously organized by the Institut de Mécanique Céleste et de Calcul des Éphémérides (Arlot et al. 1992; Arlot et al. 1997; Thuillot et al. 2001). Observing mutual phenomena and the magnitude drop during occultations and eclipses yields high-precision astrometry. In the case of the Jupiter system, Vasundhara (1991) claimed that the observations of mutual phenomena increased the astrometric precision by at least two orders of magnitude compared to photographic or eclipse (behind the planet) observations. However, this theoretical estimate seems to be optimistic; the differences between residuals issued from new astrometric observations and those obtained from mutual events show a factor of two or three improvement in precision (Figs. 3–4 in Lainey et al. 2004).

Predictions of mutual events in the Uranian system were published by Christou (2005) and Arlot et al. (2006). In their listings of best eclipses and occultations, the parameters are slightly different and dependent on the modeling of the phenomena. Besides the possible inaccuracy in the Uranian moon ephemerides, these differences could be linked

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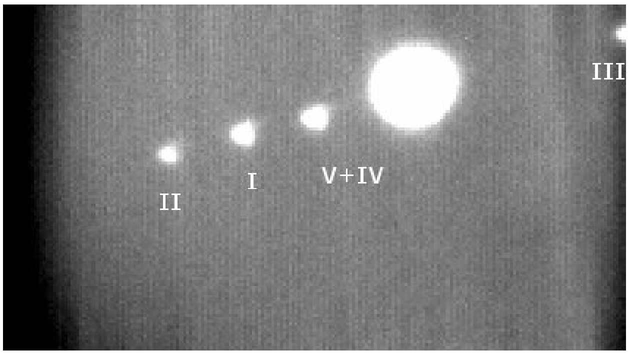


**Fig. 1** Image obtained with the CSHELL camera in the $K$ band. The exposure time was 5 s. The image shows the satellites Umbriel (UII), Ariel (UI), as well as Miranda (UV) and Oberon (UIV) as separate point sources. Both Umbriel and Ariel were used for the astrometry and the photometry of the occultation (©IRTF and IMCCE.

both to the model of the event and to the physical properties of the moons.

Through new observations we seek to improve the accuracy in the construction of theories of motion, and the ephemerides of natural satellites. In the case of the Uranian system of satellites, the observations of the mutual phenomena are particularly useful, because the high obliquity angle of the planet introduces otherwise high uncertainty in their orbital inclination.

Here we present the observation of the mutual event in the Uranian system between the satellites Miranda (UV) and Oberon (UIV). The photometry and the astrometry are discussed.

## 2 The observation of the 2007 July 30 Miranda-Oberon occultation

From the Earth, the Uranian system appears very compact (approximately 30″ for the first five satellites), since the planet system orbits at about 19 A.U. from the Sun, and the satellites are orbiting nearly in the equatorial plane of the planet. In order to avoid saturation of satellites into the diffuse light of Uranus, the observations must be done in specific wavelength bands (such is $K$ or $K'$ band) where the planet is dimmed by the strong absorption of methane. The influence of diffuse light of the rings is already minimal, as well as their being edge-on during the Uranian equinox. Thus, for long eclipses and occultations (15–60 min) the observations can be sampled using long exposure images (20-180 s), while for the quick events (1–15 min) the time sampling must be more rapid (5–10 s).

We observed the occultation between Miranda and Oberon on 2007 July 30, following the prediction of Arlot et al. (2006) using the LA06 dynamical model. This event was predicted to have a duration of 864 s and a magnitude drop of $0\overset{m}{.}07$ in the $V$ band. We emphasize that this event is mentioned in the on-line table[1] of events predicted by Christou (2005), and is also found using the GUST86 ephemeris (with a magnitude drop lower than that of LA06). Predicted parameters of the occultation following several authors and ephemerides model are presented in Table 1.

The magnitude drop of the event should be spectral band dependent ($K$ band in our case). This is related to the predicted $V$ magnitude drop if the color in the $K$ band is determined. The synthesis presented by Fry et al. (2007) shows a good agreement in reflectivity for the available data of Miranda and Oberon in the $K$ band (e.g. Kesten et al. (1998) for Miranda, and Cruikshank (1980) for Oberon). However, we can note values of the $K$ reflectivity slightly different (around $0\overset{m}{.}016$, sensible lower than the $V$ magnitude drop) for Miranda in the article of Baines et al. (1998). For our study we consider the $V$ band magnitude drop estimation also reasonable for the $K$ band.

The observations were performed using the CSHELL spectrograph camera (Greene et al. 1993) in imaging mode (http://irtfweb.ifa.Hawaii.edu/∼cshell/), and the NASA 3 metre aperture telescope IRTF, located at 4200 m altitude at Mauna Kea, Hawaii. Image acquisition and guiding were done remotely (Bus et al. 2002) from France using CODAM facilities (Birlan, Barucci & Thuillot 2004; Birlan et al. 2004). The observations were performed in the $K$ band, centered at 2.19 $\mu$m. The run was performed during a window lasting 30 min, which covered more than two times the estimated duration of the occultation. The exposure time for each image was 5 s, and 251 images similar to that presented in Fig. 1 were obtained. The calibration images (dark and flat-field) were also performed at the beginning and at the end of the run. The weather conditions were poor; the seeing conditions ranged from 1.1″ to 1.4″.

## 3 Data reduction and results

Both photometry and astrometry measurements were performed during this event. The images were subtracted by a median dark-field, and were flat-fielded by a median, normalized flat-field.

### 3.1 Photometry

Figure 1 shows a single frame containing both Oberon (UIV) and Miranda (UV). The images were reduced photometrically using several procedures, namely IRAF/DAOPHOT automatic procedure, and MIDAS (MAGNITUDE/CIRCLE, CENTER/GAUSS and CENTER/IQE). The results of relative photometry were quite similar for all data reduction procedures. The relevant results of photometry are presented in Fig. 2. The measurements are presented with error-bars, and the period of the occultation is highlighted in grey background.

The photometry results presented in Fig. 2 do not confirm the predicted magnitude drop of $0\overset{m}{.}07$. However these

[1] http://www.arm.ac.uk/∼aac/uranus/

 

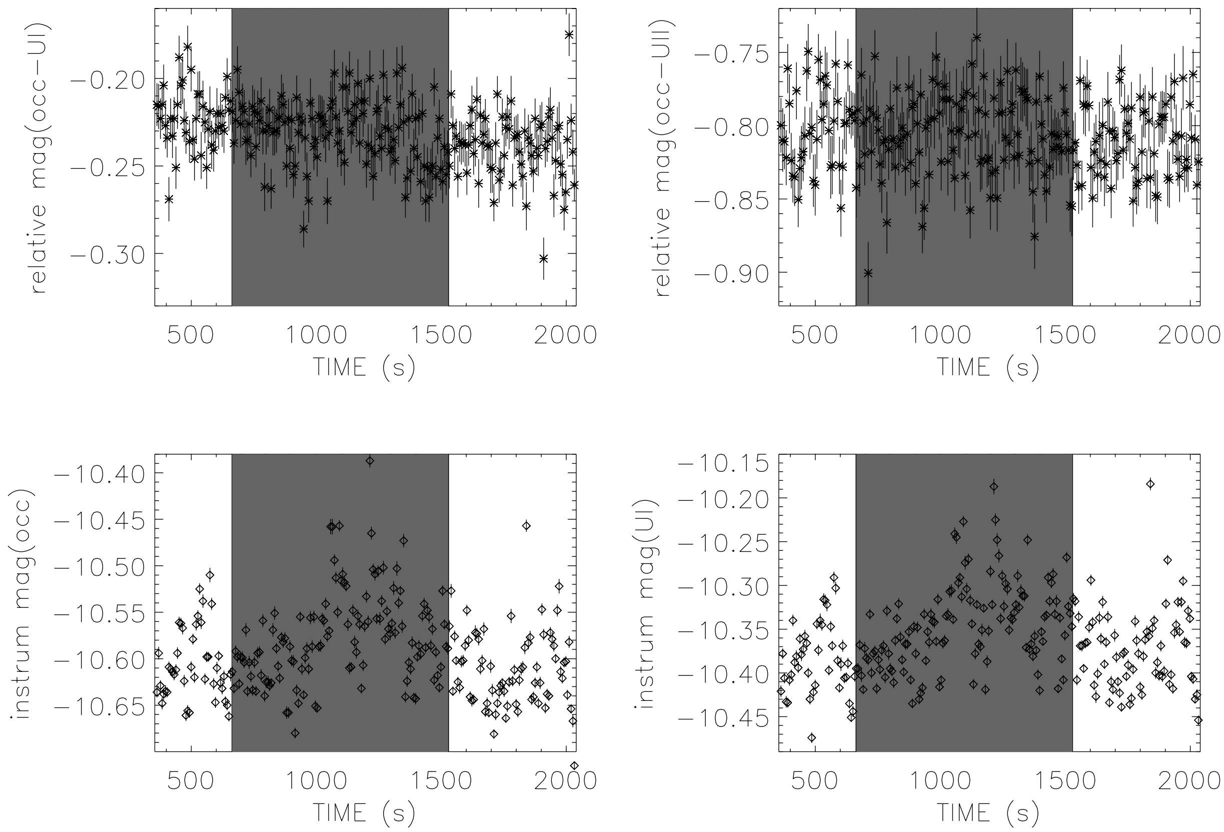


**Fig. 2** The photometry (with error bars) of the occultation Miranda-Oberon relative to UI-Ariel (*upper left*), and UII-Umbriel (*upper right*). The time is given in seconds, with the UT origin at $10^{\rm h}\,50^{\rm m}$. The background in gray represents the predicted time of the event. Instrumental magnitudes (with error bars) are presented for the system Miranda-Oberon (*lower left*) and Ariel (*lower right*) respectively.

**Table 1** Predicted parameters of the occultation between Miranda and Oberon on 2007 July 30. Reference, ephemeris, moments (in UT) and duration (in seconds) of the event, and magnitude drop are shown.

| Reference | Ephemeris | Event Start | Event End | Duration (s) | $V$ mag Drop |
|---|---|---|---|---|---|
| Arlot et al. 2006 | LA06 | 11:01:04 | 11:15:28 | 864 | 0.069 |
| Arlot et al. 2006 | GUST86 | 11:11:06 | 11:23:01 | 715 | 0.044 |
| Christou 2005 | GUST86 | 11:09:55 | 11:21:47 | 712 | 0.038 |

data provide an upper limit for the magnitude drop of $0\overset{\rm m}{.}05$, which corresponds to the dispersion of the points.

### 3.2 Astrometry

The geometric positions of the satellites were obtained together with the photometry. The astrometry was done using the procedure CENTER/IQE. This procedure gives the astrometric position taking into account two Gaussian distributions on two perpendicular axes, and takes into account a rotation of the Gaussian compared to $(x, y)$ system of the CCD camera. Our comparison with the astrometry obtained through other procedures (applied automatically and not) shows only a small shift in the homogeneous data sets, at the limit of few tenths of a pixel.

The small field of the images does not allow data astrometry using background objects. The astrometric analysis needs an external, independent determination of the scale factor for the images. Thus, the measurements are differential for the satellites UIV and UV, utilizing available positions (and ephemerides) of the satellites Ariel and Umbriel.

While astrometry was never published and performed with the CSHELL camera, and the only available value for the scale factor does not satisfy reliable astrometric accuracy, a new value was calculated. This new scale factor was obtained using a dense field of stars centered at $06^{\rm h}\,02^{\rm m}\,54^{\rm s}$ in right ascension and $+10^\circ\,27'\,00''$ in declination for J2000.0 epoch. Data reduction was performed using the 2MASS catalogue. The measurements shows a dichotomy between the $X$ scale and the $Y$ scale of 0.006 arc-

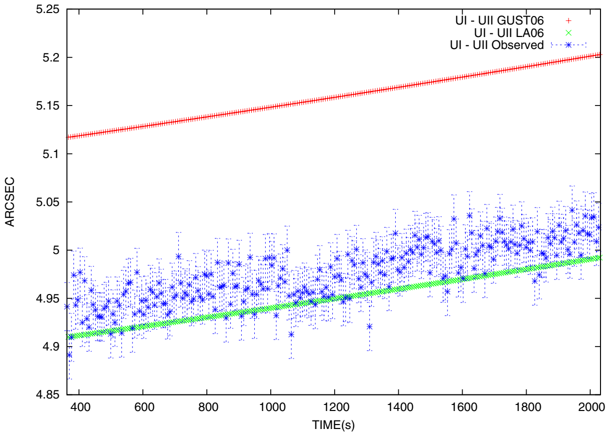


**Fig. 3** (online colour at: www.an-journal.org) The observed angular separation between UI and UII satellites (with error bars). The angular separation between the satellites ephemerides using LA06 and GUST86 (adjusted) dynamical models are represented by the straight line. The origin of time is July 30, $10^{h}\,50^{m}\,00^{s}$ UT. The ordinate represents the distance between satellites (in arcseconds).

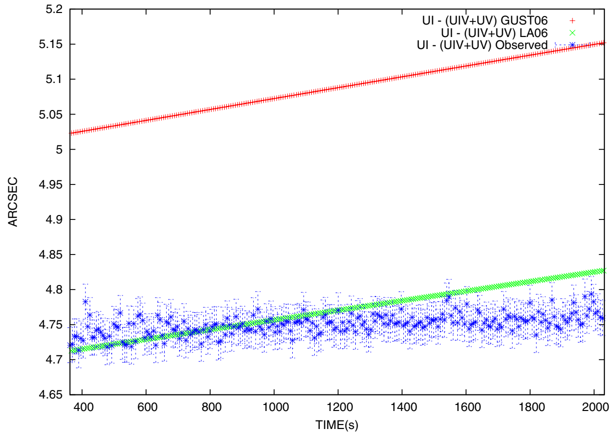


**Fig. 4** (online colour at: www.an-journal.org) The observed angular separation between UI and (UIV + UV) satellites (with error bars). The angular separation between the satellites ephemerides using LA06 and GUST86 (adjusted) dynamical models are represented by the straight line.

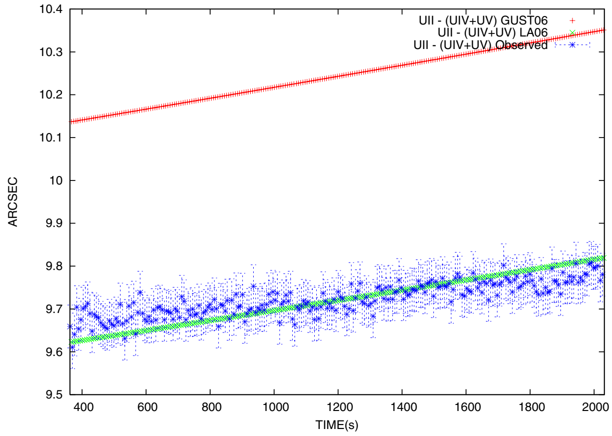


**Fig. 5** (online colour at: www.an-journal.org) The observed angular separation between UII and (UIV + UV) satellites (with error bars). The angular separation between the satellites ephemerides using LA06 and GUST86 (adjusted) dynamical models are represented by the straight line.

seconds per pixel, important for astrometric purposes. This difference in plate scale is due to an anamorphic feature of the slightly off-axis design or to a small tilt of the array to avoid CVF[2] ghosts (Rayner, private communication):

$$X_{\rm scale} = (0.1944612 \pm 0.0000012)\,''/\text{pixel}, \tag{1}$$

$$Y_{\rm scale} = (0.2000430 \pm 0.0000009)\,''/\text{pixel}. \tag{2}$$

In the computation of relative distances, both $X$ and $Y$ scales were taken into account. As shown in Fig. 1 the satellites are dispersed mainly on the horizontal (X axis), which implies that $X$ scale is the dominant factor in their relative positions. The comparison of the measurements was performed using both LA06 (Lainey 2007; Arlot et al. 2006) and GUST86 (Laskar & Jacobson 1986) dynamical models (Fig. 3) in order to check the reliability of the astrometric reduction procedure. Differences between UI and UII ephemerides were compared with the astrometry obtained from the images. The trend of the measurements follows that of the ephemerides, an expected result.

The astrometry fits very well the values obtained from LA06, proving the accuracy gain in ephemerides. This is also confirmed by the monitoring of other mutual phenomena observed in December 2007 (Arlot, private communication).

We must emphasize the high importance of the astrometric calibration of the detector. For a scale factor variation of 5%, the differences in astrometric position can be fit by one dynamical model rather than the other. Thus, for a scale factor of $0.1944\,''$/pixel, the best fit corresponds to LA06, while for a scale factor of $0.205\,''$/pixel, GUST86 is preferred.

The same procedure was applied using the measurements of the single-image complex (UIV + UV). Figures 4 and 5 present the comparison between UI and UII respectively, considering the calculated values of the ephemerides for each object in both dynamical models. The comparison of measurements with the calculated differences shows a linear tendency in which the slope is different than the one given by the ephemerides. This effect is probably the result of the centroid fitting algorithm trying to accommodate the merged images of UIV and UV as they approach and subsequently recede from each other.

### 3.3 The photometry and the noise associated with the presented event

Using LA06 ephemerides, Arlot et al. (2006) predict a magnitude drop of $0\overset{\rm m}{.}07$ for this occultation, using the assumption of spherical shapes for the bodies and the Lambertian law of scattering. Is this event detectable with the ob-

[2] Acronym of Circular Variable Filter.

 

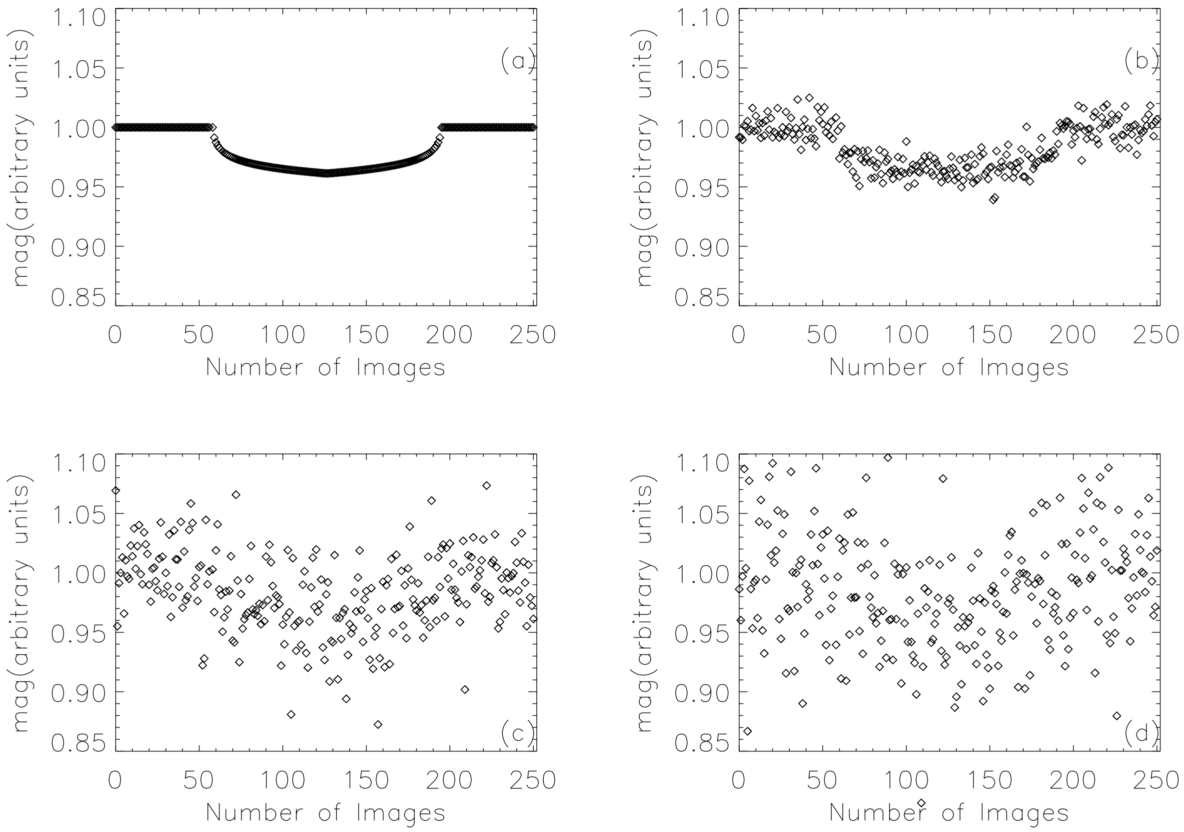


**Fig. 6** A model of a theoretical occultation between Miranda and Oberon (*a*), contaminated by a Gaussian noise of $0^{\mathrm{m}}.01$ (*b*), $0^{\mathrm{m}}.03$ (*c*), and $0^{\mathrm{m}}.05$ (*d*).

tained data-set? The first approach to constrain the detection of a "real" event is to account for the noise induced into the signal by various sources (terrestrial atmosphere, telescope and CCD characteristics, CCD electronics, interplanetary medium, etc.). In this case, we considered a synthetic representation of the phenomenon perturbed by a simple white noise, with variable amplitudes. The model of an actual event was obtained as a result of the addition of the theoretical model of the phenomenon and the noise. Figure 6 presents the results with amplitudes of $0^{\mathrm{m}}.01$, $0^{\mathrm{m}}.03$, and $0^{\mathrm{m}}.05$ in the Gaussian noise. The number of points are equidistant in time and equal to the number of images obtained by the real observation, and the interval of the phenomenon match the predicted one. As can be seen, the white noise at a level of $0^{\mathrm{m}}.05$ makes it difficult to detect such an event. As seen in Fig 2, this corresponds with the level of noise of our data.

This simulation gives the possibility to speculate on the observability of these phenomena. The modeling of the photometric data with the right (Gaussian) filter, considering the theoretical model of the occultation may give new insight for this investigation. Some tests were performed in our analysis but this analysis is still under development.

Finally, the conclusions of our analysis will be probed by the analysis of future mutual events of UIV by UV. More than ten such events will occur during the Uranus equinox.

## 4 Conclusions

The observation of the predicted occultation of Oberon by Miranda on 2007 July 30 was monitored leading to results in astrometry (thanks to the measurement of the relative distances between the satellites during the event) and in photometry. No event was seen on the recorded light curve but results on the ephemerides accuracy may be derived from these observations. We showed in the previous sections that we were not able to record an event whose magnitude drop is less than $0^{\mathrm{m}}.05$. Thus, the result of our observation is that the magnitude drop of the occultation of Oberon by Miranda is less than $0^{\mathrm{m}}.05$.

The predictions were made using two models: GUST86 and LA06. GUST86 predicted a magnitude drop of $0^{\mathrm{m}}.04$, while LA06 predicted a magnitude drop of $0^{\mathrm{m}}.07$. One interpretation of the observations is that the LA06 prediction was off by at least $0''.02$ in this case. Nothing could be deduced for the GUST prediction. Another explanation may be that the scattering law on the surface of Oberon is different from the Lambertian one used for the computation.

As regarding the astrometry, the measurement of the distances show that the LA06 ephemeris is in better agreement with the observations than the GUST86 ephemeris.

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