Astronomy & Astrophysics manuscript no. pheura07-catal4
February 7, 2013

Astrometric results of observations of mutual occultations and eclipses of the Uranian satellites in 2007

J.-E. Arlot[1], N. V. Emelyanov[2,1], Z. Aslan[3], J. Bel[4], B.C. Bhatt[5], T. Brown[6], R. Casas[7], A. Christou[8], F. Colas[1], J.F. Coliac[9], C. Dumas[10], C. K. Ellington[11], E. Forne[12], E. Frappa[23], E. Gomez[13], K. Gourgouliatos[14], M. Hidas[6], I. Khamitov[3], F. Lewis[13], C. Miller[15], R.J. Modic[16], Dk. Sahu[5], B. Sicardy[17], P. Tanga[18], V. Tsamis[19], P. Valdes Sada[21], R. Vasundhara[5], R. Vieira-Martins[20], H. Worters[22]

[1] Institut de mécanique céleste et de calcul des éphémérides – Observatoire de Paris, UPMC, USTL, UMR 8028 du CNRS, 77 avenue Denfert-Rochereau, 75014 Paris, France
e-mail: `arlot@imcce.fr`
[2] Lomonosov Moscow State University, Sternberg Astronomical Institute, 13 Universitetskij prospect, 119992 Moscow, Russia
e-mail: `emelia@sai.msu.ru`
[3] Tubitak National Observatory, Akdeniz Universitesy Yerleskesi, 07058, Antalya, Turkey
[4] Ager, Lleida, Spain
[5] Indian Institute of Astrophysics, Bangalore, India
[6] Las Cumbres Observatory Global Telescope, 6740 Cortona Dr. Ste. 102, Goleta, CA 93117, USA
[7] P.O. Box 50, 08200 Sabadell, Spain
[8] Armagh Observatory, College Hill, Armagh BT61 9DG, Northern Ireland
[9] Marseille, France
[10] ESO, Chile
[11] Covington, Seattle, WA, USA
[12] L'Ampolla, Tarragona, Spain
[13] Faulkes Telescope Project School of Physics and Astronomy, Cardiff University, Queens Buildings, 5 The Parade, Cardiff CF24 3AA, UK
[14] Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
[15] Apache Point Observatory, 2001 Apache Point Road, P.O. Box 59, Sunspot, NM, USA
[16] Cleveland, Ohio, USA
[17] LESIA, Paris observatory, Meudon, France
[18] Observatoire de la Côte d'Azur, France
[19] Hellenic Astronomical Association, I. Metaxa and Vas. Pavlou Str., Palaia Penteli Attikis, 15236 Athens, Greece
[20] Rio de Janeiro Observatory, Brazil
[21] Universidad de Monterrey, Departamento de Fisica y Matematicas, Av. I. Morones Prieto 4500 Pte., San Pedro Garza Garcia, N.L., C.P. 66238, Mexico
[22] Southern African Large Telescope Foundation, P.O. Box 9, Observatory, 7935, South Africa
[23] Planétarium de Saint-Etienne, 28 rue Ponchardier F-42100 Saint-Etienne

Received XX xxxxx 20XX / Accepted XX xxxxx 20XX

ABSTRACT

Context. The photometry of mutual occultations and eclipses of natural planetary satellites can be used to infer very accurate astrometric data. This can be achieved by processing the light curves of the satellites observed during international campaigns of photometric observations of these mutual events.tellites.
Aims. This work focuses on processing the complete database of photometric observations of the mutual occultations and eclipses of the Uranian satellites made during the international campaign in 2007. The final goal is to derive new accurate astrometric data.
Methods. We used an accurate photometric model of mutual events adequate of accuracy of observation. Our original method is applied to derive astrometric data from photometric observations of mutual occultations and eclipses of the Uranian satellites.
Results. We process the 39 light curves obtained during the international campaign of photometric observations of the Uranian satellites in 2007. As compared with the theory, the r.m.s. 'O-C' residuals with respect to theory for the best 32 observations are equal to 10.3 and 16.4 mas in right ascension and declination, respectively.
For 5 observations the position angle only was derived. Topocentric or heliocentric angular differences for satellites pairs are obtained for 25 time instants during the time period from May 4, 2007 to January 4, 2008.

Key words. ephemerides – planets and satellites: general

1. Introduction

Photometric observations of mutual occultations and eclipses of natural satellites of planets offer an efficient source of new astrometric data. The accuracy of the observation of phenomena depends mainly on our knowledge of thge size of the objects and their shadows. So, this accuracy is provided in kilometers and does not depend on the distance between the objects and the Earth. Then, farther are the objects, better is the accuracy in angle. This especially true for the Uranian satellites.

2. The mutual events

The Earth and the Sun traverse the equatorial plane of Uranus every 42 years (at the equinox). The uranocentric declinations of the Earth and the Sun then become zero and, since the orbital plane of the satellites is close to the equatorial plane of Uranus, the satellites occult and eclipse each other.

Fortunately, this equinox occurs in 2007 and the period was particularly favorable because the equatorial plane crossing occurred near the conjunction of Uranus and the Sun.

Arlot et al. (2006) compiled predictions of all 2006-2009 events using the LA07 ephemerides based upon recent observations. About 280 possible mutual events were computed even only 170 were easily observable. These observations are difficult because of the proximity of the planet Uranus. Specific infra red filters were recommended in order to increase the possible observations. However, our goal was to observe as many events as possible and recommendations were given (Arlot and Sicardy, 2008). Two observations of each event were at least desirable to eliminate any biases in the observation.

Since no thick atmosphere surrounds any of the Uranian satellites, the photometric observations of these phenomena are extremely accurate for astrometric purposes . More, the large distance to the Earth will make the accuracy in angle much better than for direct imaging astrometric observations.

This fact allows us to provide data very essential data to improve the theoretical models of the orbital motions and the dynamics of the Uranian satellites.

3. The PHEURA07 campaign

We coordinated an international PHEURA07 campaign to acquire a significant amount of events. These events occur in a short period of time, so numerous observers located in several sites were necessary to both help avoid meteorological problems and observe different events from different longitudes. However, observations were more difficult than with the Galilean satellites which present similar events: the closeness of the planet Uranus prevents to observers events occurring close to the planet. Infra red techniques allowing such observations will require large telescopes. Note that the negative value of the declination of Uranus (around -8 degrees) favored the Southern hemisphere observers.

3.1. Receptors

When observing mutual events, only relative photometry can generally be completed. Since the elevation of Uranus above the horizon may be small, the air mass is often too high and absolute photometry is then impossible. Telescopes were equipped with the receptors listed in Table 1.

Table 1. Receptors used for the observations

Code as given in the tables	Description
CCD0	unknown
CCD1	camera SBIG ST-9XE
CCD2	Atik 16 Ic
CCD3	NACO (ESO Paranal UT4 telescope)
CCD4	Santa Barbara Instrument STL1301-E
CCD5	SITE ST-002 camera
CCD6	SBIG ST7-XME
CCD7	CCD Kodak Kaf 400L
CCD8	Agile High Speed photometer (APO telescope)
CCD9	Starlight SXV-H9
CCD10	CCD FLI-CM9
CCD11	wmv movie from video camera
CCD12	CCD Thomson THX 7863, 388 284 pixel

3.2. Sites of observation

Coordinated by the IMCCE, this campaign involved the different locations given in Table 2. This table gives the names, longitudes, latitudes, and elevations of the observational sites and the telescopes used (L means refractor and T means reflector, followed by the aperture in cm).

4. Lightcurves reduction procedure

Light curves were deduced from photometric measurements performed with CCD cameras. For observations completed with CCD cameras in analogic video mode, the signal was digitized with digitizing boards. For observations recorded with video cameras on a numeric file movie, specific softwares were used for separating all images before photometric analysis. The light curves were obtained most of time by aperture photometry. Two dimensional measurements generally allow us to calibrate the signal from a particular satellite to that from a nearby satellite and eventually to acquire data under difficult conditions such as twilight or light clouds (Arlot and Stavinschi, 2007). We will provide in the next sections two different results: first the photometric results as magnitude drops

Table 2. Sites of observation for the PHESAT09 campaign

Sites	Code	Tel.	Rec.	Longitude ° ′ ″	Latitude ° ′ ″	elevation meters
Ager, Lleida (Spain)	AGE	T 100	CCD1	0 44 43 E	42 01 12 N	749
Ampola, Tarragona (Spain)	AMP	T 36	CCD9	0 40 13 E	40 48 26 N	15
Apache Point, New Mexico (USA)	APO	T 250	CCD8	105 49 13 W	32 46 49 N	2788
Athens (Greece)	ATH	T 40	CCD0	23 53 36 E	37 59 52 N	0
Cleveland, Ohio (USA)	CLE	T 40	CCD6	81 04 52 W	41 32 48 N	389
Covington, Seattle, WA (USA)	COV	T 100	CCD11	122 9 34 W	47 21 36 N	124
Faulkes South, Siding Spring (Australia)	FAS	T 200	CCD0	149 3 42 E	31 16 24 S	1149
Faulkes North, Haleakala, Maui, Hawaii (USA)	FAU	T 200	CCD0	203 44 45 E	20 42 27 N	3055
Hanle (India)	HAN	T 200	CCD5	78 57 54 E	32 46 46 N	4500
Itajuba (Brazil)	ITA	T 160	CCD0	45 35 0 W	22 32 6 S	1870
Marseille (France)	MAR	T 20	CCD2	5 23 09 E	43 18 32 N	50
Monterrey (Mexico)	MON	T 35	CCD4	100 20 46 W	25 37 23 N	689
NTT, ESO-La Silla (Chile)	NTT	T 350	CCD0	70 43 54 W	29 15 40 S	2400
Pic du Midi (France)	PIC	T 100	CCD0	0 08 34 E	42 56 11 N	2850
Sabadell, Barcelona (Spain)	SAB	T 50	CCD10	2 05 29 E	41 33 04 N	224
SALT, Sutherland (South Africa)	SUT	T 1000	CCD0	20 48 38 E	32 22 33 S	1771
TNG, Canarian Islands (Spain)	TNG	T 360	CCD0	17 53 38 W	28 45 28 N	2387
Tubitak, Antalya (Turkey)	TUB	T 150	CCD0	30 20 8 E	36 49 27 N	2500
VLT, ESO-Paranal (Chile)	VLT	T 800	CCD3	70 24 15 W	24 37 38 S	2635

and timing of the minimum of light (which is not the minimum of distance because if the phase effect) and second the astrometric relative positions of the satellites as deduced from the light curves.

5. The photometric data

The determination of both the time of minimum light and the extent of the magnitude drop were based on a fit to the light curve of a sample polynomial. The errors in these determinations are also given. The error in the timing of the minimum is determinated as follows: we calculate the noise in magnitudes and transform it into a time error through the highest value of the speed of decreasing in magnitude during the event. The largest errors occur during the faint noisy events and the smallest for the most rapid. The errors remains comparable only if the integration times are the same. Table 3 provides, for each event, the observed midtime and the corresponding magnitude drop. The filters used for each observation is also given. Note that the filter L (or Large filter) corresponds often to no filter at all. In that case, the light is filtered by the sensitivity profile of the target. The satellites the flux of which being measured are indicated in the last column. Figure 1 shows all the observed light curves. All the photometric data are available on www/imcce/fr/nsdc. The next section will provide the astrometric data extracted from the light curves.

6. Extracting astrometric data from the photometry of mutual events. General assumptions

We use our original method to derive positional and astrometric data from the measurements of satellite fluxes during their mutual occultations and eclipses. The main idea of the method consists in modelling the deviation of the observed relative satellite motion from the theoretical motion provided by the relevant ephemeris rather than analysing the apparent relative motion of one satellite with respect to the other.

The measured flux E during an event at a given time t may be expressed by

$$E(t) = K \cdot S(X(t), Y(t)),$$

where $X(t)$ and $Y(t)$ are the projections of the differences of planetocentric Cartesian coordinates of the two satellites onto the tangent plane of the event. The function $S(x, y)$ describes a model of the phenomenon. It is supposed $S(x, y) = 1$ off event. The parameter K is a scale factor for the light drop during the event and it is equal to the total flux outside the event.

Given appropriate theories of the motion of planets and satellites, one can compute the theoretical values of functions $X(t), Y(t)$, i.e., $X_{th}(t), Y_{th}(t)$ for the time $t_i (i = 1, 2, ...m)$ of each photometric measurement. Here m is the number of photometric counts during a single event. The real values of $X(t_i)$ and $Y(t_i)$ differ from $X_{th}(t)$ and $Y_{th}(t)$ by corrections D_x, D_y. Our method consists of solving conditional equations

$$E_i(t) = K \cdot S(X_{th}(t_i) + D_x, Y_{th}(t_i) + D_y) \quad (i = 1, 2, ...m) \quad (1)$$

Table 3. Filters and observed satellites.

UTC Date year m. day	Type of event	Site of obs.	Filter	Sat.
2007 5 4	4o2	FAS	I’	4-2
2007 7 26	1e5	FAS	I’	1-5
2007 8 5	4o2	FAU	I’	4-2
2007 8 6	1o5	FAU	I’	1-5
2007 8 6	4o2	TNG	I	4-2
2007 8 13	1o2	ITA	I	1-2
2007 8 13	1o2	CLE	-	1-2
2007 8 13	1o2	NTT	K’	1-2
2007 8 13	1o2	PIC	DH710B	1-2
2007 8 14	2o4	ATH	IR72	2-4
2007 8 14	2o4	ITA	I	2-4
2007 8 14	2o4	TUB	Ic	2-4
2007 8 15	2o3	APO	I	2-3
2007 8 15	2o3	COV	R	2-3
2007 8 15	2o3	NTT	K’	2-3
2007 8 19	2o1	APO	I	2-1
2007 8 19	1o2	MON	R	2-1
2007 8 19	2o1	NTT	K’	2-1
2007 8 19	2o1	ITA	I	2-1
2007 8 22	2e5	FAU	I’	2-5
2007 8 24	1o2	FAU	I’	1-2
2007 10 8	1o5	ITA	I 7	1-5
2007 10 12	3e5	ITA	I	3-5
2007 10 12	4e5	FAU	I’	4-5
2007 11 28	1e3	ITA	I	1-3
2007 11 30	1e5	FAU	I’	1-5
2007 11 30	3e4	AGE	L	3-4
2007 11 30	3e4	AMP	Bessell R	3-4
2007 11 30	3e4	MAR	V	3-4
2007 11 30	3e4	SUT	Bessell I	3-4
2007 11 30	3e4	SAB	-	3-4
2007 12 4	2e1	APO	I	2-1
2007 12 7	1e2	APO	I	1-2
2007 12 7	1e2	MON	R	1-2
2007 12 8	2e3	MON	R	2-3
2007 12 8	2e3	VLT	K’	3
2007 12 15	1e3	HAN	Z	1-3
2007 12 17	4e3	HAN	Z	4-3
2008 1 4	1e5	TUB	Ic	1-5

for parameters D_x, D_y, and K. Here E_i is the photometric recorded at time t_i. We linearize conditional equations with respect to parameters D_x, D_y and then solve them using the least-square method.

The function $S(x, y)$ is calculated as an integral of the flux from each point of satellite over the hemisphere facing the Earth. For each point we consider wavelengthdependent reflective properties of the satellites, various laws of light scattering by a rough surface, variation of reflective properties over the satellite surface, wavelengthdependent solar limb darkening. We consider also a wavelength-dependent sensitivity of the detector.

See (Emelyanov, 2000, 2003; Emelyanov & Gilbert, 2006) for a description of the method, which we have already used in our works (Emelyanov, 2009).

Table 4. Results of the fit of the photometric parameters to the observed reflectivities.

Satellite	A_0	β	α_0	γ
U1 Ariel	0.533	0.0250	0.200	0.140
U2 Umbriel	0.248	0.0385	1.152	0.060
U3 Titania	0.357	0.0449	0.525	0.308
U4 Oberon	0.277	0.0363	1.675	0.316
U5 Miranda	0.488	0.0471	0.182	-0.084

7. Adopted photometric model of the satellites

The most comprehensive available data about the photometric properties of the major satellites of Uranus are published in (Karkoschka, 2001). In this paper the results of the direct photometric measurements of satellites with the different phase angles and for the different wavelengths, and also the parameters of Hapke phase function are given. This allowed us to test the application of two light scattering laws — the Lommel–Seeliger and Hapke laws.

As we have not find a reliable data for variation of reflective properties over the satellite surface we supposed a uniform surface of satellite.

In the application of the Lommel–Seeliger law we search for a dependence of satellite albedo on the phase angle and light wavelength. According to Karkoschka (2001) this dependence can be as following

$$A = A_0[1 + \gamma(\lambda - 0.55)]10^{-0.4(\beta\alpha + 0.5\alpha/(\alpha_0+\alpha))} \qquad (2)$$

where α is the phase angle measured in degrees, λ is the light wavelength measured in μm, and $A_0, \gamma, \beta, \alpha_0$ are the photometric parameters of satellite. We can identify A with the observed reflectivity which besides the dependence of albedo on the phase angle includes also the phase effect considered by the Lommel–Seeliger law. Values of the photometric parameters are given in (Karkoschka, 2001). Nevertheless we preferred to make the independent fit of the parameters to the observed reflectivities given in the Table V by Karkoschka (2001).

In 2007 the phase angle for Uranus was less than 0.21 degrees only from 6 Sep. 2007 to 13 Sep. 2007. There is no observation of the mutual events on this time interval. Therefore the observed reflectivities at the phase angle 0.21, 1.10, 2.82 degrees only could be taken for the fit of the parameters. The results of our fit are given in the Table 4. For the satellite U1 Ariel the fit of all parameters was not successful and we took the parameters A_0, β, α_0 from (Karkoschka, 2001) but refined only γ.

Using the obtained values of the parameters and the function (2) we could apply Lommel–Seeliger law to deduce astrometric results from the photometric observations of the mutual events of the satellites. However it is necessary to explain what of two light scattering laws — the Lommel–Seeliger and Hapke laws is better to use.

¿From all available observations we selected for our test the most precise photometric observations which were made in the observatory Apache-Point 15 August, 2007.

Table 5. Agreement of observations with the model (σ_S) and the resulting minimum of the apparent distance between the satellites (r_{min}) for different light scattering laws adopted.

Light scattering law adopted	r_{min} km	σ_S
Lommel-Seeliger law	62	0.0102
Hapke law	184	0.0115
Hapke law with corrected albedo	67	0.0103

The occultation of Titania by Umbriel was there observed. ¿From these photometric observations astrometric data are derived via an advanced method incorporating light scattering laws in two cases – the Lommel–Seeliger and Hapke laws. In the case of Hapke law the relevant parameters were taken from (Karkoschka, 2001) but the albedos of the satellites were reduced to the wavelength of the filter I used in the Apache-Point observatory. The minimum distance r_{min} between centers of the apparent disks of satellites during the event was undertaken as astrometric result for the comparison.

In order to estimate the quality of the agreement of observations with the model the rms value σ_S of the deviations of the normalised measured flux S from the model light curve was calculated for the moments of measurements inside the phenomenon. In the case of mutual occultation the astrometric result depends directly on the relation of the albedo of two satellites. In two cases of the light scattering law these relations were calculated and they proved to be distinguishing by the coefficient of 0.88. Therefore the second comparison was made after correction of the albedo on this coefficient. The results of the comparison are given in the Table 5.

It is evident from the table that the astrometric result strongly depends on the albedo of satellites and considerably less from the accepted light scattering law. With the parameters given in (Karkoschka, 2001) Hapke law does not give better agreement of the photometric measurements with the model. As emphasized Karkoschka (2001) "Different combinations of parameters of the five-parameter model can yield almost identical phase curves, making a fit very sensitive to observational errors". Therefore we cannot consider the Hapke parameters reliable. In fact we decided to use Lommel–Seeliger law with the function (2) for the albedo and the parameters from the Table 4.

Concerning the albedo dependence on the rotation of satellite the observed rotational features given in (Karkoschka, 2001) are not sufficiently precise to be used in our application.

8. Astrometric parameters

Along with Cartesian coordinates X, Y one can also consider angular coordinates X'' and Y'' defined by the equations

$$X''(t^*) = \Delta\alpha \cos\delta_p, \quad Y''(t^*) = \Delta\delta,$$

$$\Delta\alpha = \alpha_a - \alpha_p, \quad \Delta\delta = \delta_a - \delta_p,$$

where α_a, δ_a are the right ascension and declination of occulting or eclipsing satellite, α_p, δ_p are the corresponding coordinates of the occulted or eclipsed satellite. In the cases of mutual eclipses these coordinates are heliocentric.

Precise relationships between X'', Y'' and X, Y are find in (Emel'yanov, 1999). Given the topocentric or heliocentric distances R of the satellites one can compute X'', Y'' from X, Y using approximate relations

$$\tan X'' = X/R, \quad \tan Y'' = Y/R$$

which are accurate for the considered observations to 0.00001 arcseconds.

In a similar way we designate by D''_x, D''_y the angular values corresponding to the corrections D_x, D_y.

After the solution of the equations (1) the astrometric result of the observation is derived as the corrected relative position of satellites $X''(t^*) = X''_{th}(t^*) + D''_x, Y''(t^*) = Y''_{th}(t^*) + D''_y$ together with the associated time instant t^* inside the time interval of the event. Although this is not mandatory, we assume that t^* is the time instant when $\sqrt{X^2 + Y^2}$ takes its minimum value, i.e., t^* is the time of the closest apparent approach of the satellites.

The errors σ_x and σ_y of the parameters D''_x, D''_y estimated via the least-square method can be interpreted then as internal errors of the astrometric results following from the random errors of the photometry.

The derived values D''_x, D''_y are the residuals (O-C) with respect to the applied theory of satellite motion. In our applications we used the theory Lainey (2008). This model was made with the numerical integration and is based on a large series of observations.

9. Derived astrometric results

We subdivide our final astrometric results into two sections. The first section includes the results obtained from the observations where two coordinates $X''(t^*)$, $Y''(t^*)$ could be successfully determined. The second section contains the results obtained in the cases where only position angle could be determined.

In the first section every final result of the observation of a single mutual phenomenon at a given observatory consists of the following fields: date, the type of the phenomenon (eclipse or occultation) including the satellite numbers, observatory code, the time instant t^* in the UTC scale, $X''(t^*)$, $Y''(t^*)$, σ_x, σ_y, D''_x, D''_y. The type of phenomenon is coded as $n_a o n_p$ or $n_a e n_p$ for a mutual occultation or eclipse, respectively. Here n_a is the number of the occulting or eclipsing satellite and n_p is the number of the occulted or eclipsed satellite. We give the results in the form of the angular separation s (in arcseconds) and position angle A (in degrees) corresponding to $X''(t^*)$, $Y''(t^*)$. The minimum level S_{min} of normalized flux is also given. We assign flag Q to each observation in order to indicate the quality and the reliability of the result. Flag Q may have acquire one of the following tree values: '0' for

Table 7. Second section of astrometric results (A – results, σ_{along} – random errors).

Date year, m., day	Ty- pe	Obs code	Time, h, m, s, UTC	A deg	σ_{along} mas
2007 8 13	1o2	CLE	3 5 47.35	66.46	2.8
2007 8 13	1o2	NTT	3 4 37.22	74.78	3.2
2007 8 19	2o1	MON	7 59 45.45	254.56	1.5
2007 8 22	2e5	FAU	15 3 29.40	69.13	1.6
2007 10 8	1o5	ITA	0 43 39.52	75.01	2.1

normally determined coordinates and '1' for the results obtained from poor photometric data.

Right ascensions and declinations are measured in the ICRF. All angular quantities are in arcseconds. In the case of a mutual occultation t^* is the time of topocentric observation of satellites. In the case of mutual eclipse t^* is the time of topocentric observation of the eclipsed satellite. Table 6 gives the first section of astrometric results.

The data in the second section consists of the following set of fields: date, the type of the phenomenon (eclipse or occultation) including the satellite numbers, the code of observatory, moment of time t^* in the UTC scale, position angle A, precision σ_{along} of apparent position along the apparent relative trajectory of the satellite as obtained with the least-square method. Position angle A is given in degrees and σ_{along} is given in arcseconds. In these cases the apparent relative position of the satellite measured across the apparent trajectory can not be determined accurately enough and therefore position angles can be determined only up to ±180° ($A \pm 180°$). Table 7 gives the second section of the astrometric results.

Tables 6 and 7 are available in electronic form from Natural Satellites Data Center service at http://www.imcce.fr/nsdc and http://www.sai.msu.ru/neb/nss/index.htm.

10. Estimation of the accuracy of the derived astrometric results

The following estimates of the accuracy of the derived astrometric results were made. The least-squares method yields standard errors for the parameters D''_x, D''_y derived from the observed light curves. These errors are due to random errors of photometry and characterize the internal accuracy of astrometric results. We have calculated the r.m.s. values of these estimates for all the light curves reduced to determine two coordinates $X''(t^*)$, $Y''(t^*)$. Only 32 good results with $Q = 0$ were taken into consideration. These estimates are listed in the Table 8 as total random errors. We have also calculated the total r.m.s. of all D''_x and D''_y computed over all events and all observatories for the 32 cases where two coordinates $X''(t^*)$, $Y''(t^*)$ were derived with $Q = 0$. These estimates are given in the Table 8 as r.m.s. of O-C.

Table 8. Estimates of the accuracy of the results of astrometric reduction performed to determine two coordinates $X''(t^*)$, $Y''(t^*)$.

Type of total error estimates	Errors of X'' mas	Errors of Y'' mas
Total random errors	6.6	4.1
R.m.s. of O-C	10.3	16.4

11. Conclusions

We reduced the entire database of photometric observations of the mutual occultations and eclipses of the uranian satellites made during the international campaign in 2007 to determine the topocentric or heliocentric angular differences for satellites pairs at 25 time instants on the time interval from May 4, 2007 to January 4, 2008. The standard errors of the relative satellite coordinates due to the random errors of the photometry are equal to 6.6 and 4.1 mas in right ascension and declination, respectively. The r.m.s. of 'O-C' residuals with respect to the theory by Lainey (2008) are equal to 10.3 and 16.4 mas in right ascension and declination, respectively, for successful observations. For 5 observations the position angle only was derived.

Acknowledgements. This work was supported by the FP7 ESPACE European program , the GRAM-INSU CNRS program, the Scientific Council of Paris Observatory and by the Russian Foundation for Basic Research, project no. 12-02-00294

References

Arlot J.E., Lainey V., Thuillot W.: 2006, Predictions of the mutual events of the Uranian satellites occurring in 2006-2009 Astronomy and Astrophysics, V. 456. P. 1173-1179.

Arlot, J.E., Stavinschi M. : 2007, Past and Future Mutual Events of the Natural Planetary Satellites: Need of a Network of Observation Solar and Stellar Physics Through Eclipses ASP Conference Series, Vol. 370, Astronomical Society of the Pacific, p.58

Arlot J.E., Sicardy B.: 2008, Predictions and observations of events and configurations occurring during the Uranian equinox Planetary and Space Science, Volume 56, Issue 14, p. 1778-1784.

Emelianov N.V.: 1999, Relationship between Astrometric and Theoretical Coordinates of Planetary Satellites. Solar System Research, V. 33. P. 133-137.

Emel'yanov N. V.: 2000, Determining Planetocentric Positions of Planetary Satellites from Photometry of Their Mutual Occultations and Eclipses. Solar System Research, V. 34. N. 3. P. 226-234.

Emelianov N.V.: 2003, A Method for Reducing Photometric Observations of Mutual Occultations and Eclipses of Planetary Satellites Solar System Research, Vol. 37. No.4. P. 314-325.

Emelyanov N. V., Gilbert R.: 2006, Astrometric results of observations of mutual occultations and eclipses of the Galilean satellites of Jupiter in 2003 Astronomy and Astrophysics, V. 453. P. 1141-1149.

Table 6. First section of astrometric results ($X''(t^*)$, $Y''(t^*)$ – results; σ_x, σ_y – random errors; D''_x, D''_y – O-C).

Date year, m., day	Ty-pe	Obs code	Time (t^*) UTC h, m, s	$X''(t^*)$ mas	$Y''(t^*)$ mas	σ_x mas	σ_y mas	D''_x mas	D''_y mas	s mas	A deg	Q	S_{min}
2007 5 4	4o2	FAS	19 9 56.13	28.1	7.6	2.0	1.9	-8.9	-12.2	29.2	74.84	0	0.751
2007 7 26	1e5	FAS	19 12 56.93	-25.9	-11.0	3.2	3.6	-13.6	-144.7	28.2	246.88	1	0.891
2007 8 5	4o2	FAU	13 53 48.81	59.7	16.7	1.4	1.9	-1.8	12.0	62.0	74.33	0	0.896
2007 8 6	1o5	FAU	10 35 30.86	-38.0	-7.2	2.7	4.8	-21.9	-13.8	38.7	259.18	0	0.935
2007 8 6	4o2	TNG	1 9 0.47	51.0	14.0	0.6	0.8	-13.6	-10.5	52.9	74.62	0	0.858
2007 8 13	1o2	ITA	3 6 4.67	7.9	2.1	0.5	0.2	-2.7	-09.6	8.2	74.75	0	0.698
2007 8 13	1o2	PIC	3 5 56.52	-12.0	-3.2	3.6	2.4	-23.2	-12.9	12.4	254.77	0	0.720
2007 8 14	2o4	ATH	1 34 25.00	49.7	13.5	5.2	7.0	-7.8	-19.7	51.5	74.75	0	0.816
2007 8 14	2o4	ITA	1 34 0.88	52.7	14.3	0.4	0.5	-7.6	-9.4	54.6	74.76	0	0.828
2007 8 14	2o4	TUB	1 34 4.15	55.5	15.1	2.3	3.2	-4.3	-9.8	57.5	74.76	0	0.846
2007 8 15	2o3	APO	9 16 38.95	-4.3	-1.1	0.6	0.1	5.1	-8.6	4.4	254.76	0	0.603
2007 8 15	2o3	COV	9 17 13.85	-27.1	-7.3	7.4	6.6	-14.3	-27.5	28.1	254.79	0	0.673
2007 8 15	2o3	NTT	9 15 50.17	-28.7	-7.8	1.1	1.1	-24.1	2.4	29.7	254.80	0	0.678
2007 8 19	2o1	APO	7 59 50.46	-33.1	-9.1	0.0	0.0	3.2	-6.1	34.4	254.55	0	0.680
2007 8 19	2o1	NTT	8 0 15.10	-35.5	-9.8	0.4	0.5	1.9	-10.9	36.8	254.56	0	0.702
2007 8 19	2o1	ITA	7 59 54.57	-31.4	-8.6	0.1	0.1	5.1	-6.3	32.6	254.55	0	0.663
2007 8 24	1o2	FAU	12 24 10.74	-58.4	-15.7	1.5	3.3	-2.3	-15.5	60.5	254.95	0	0.941
2007 10 12	3e5	ITA	0 3 49.39	-56.3	-12.4	1.6	4.2	-17.1	-60.2	57.6	257.51	0	0.970
2007 10 12	4e5	FAU	9 51 52.57	-22.5	-7.3	10.9	6.4	0.9	-16.7	23.7	252.07	0	0.888
2007 11 28	1e3	ITA	1 41 46.81	-57.1	-15.3	1.9	3.1	0.8	-11.3	59.1	254.96	0	0.899
2007 11 30	1e5	FAU	8 53 57.09	5.9	1.1	30.0	8.3	-17.8	-20.8	6.0	78.75	0	0.880
2007 11 30	3e4	AGE	18 54 6.06	18.9	46.2	13.5	3.6	52.4	9.6	50.0	22.26	1	0.799
2007 11 30	3e4	AMP	18 48 39.97	-27.9	-7.4	3.2	3.1	-5.9	-0.9	28.8	255.06	0	0.699
2007 11 30	3e4	MAR	18 48 16.64	-29.2	-7.7	14.1	14.9	-7.0	-2.0	30.2	255.06	0	0.756
2007 11 30	3e4	SAB	18 48 45.72	-24.5	-6.5	1.4	0.8	-2.3	-0.8	25.4	255.06	0	0.680
2007 11 30	3e4	SUT	18 48 43.37	-32.8	-8.7	0.4	0.4	-10.7	-2.6	34.0	255.06	0	0.725
2007 12 4	2e1	APO	5 5 35.25	-15.9	-4.3	0.3	0.2	-1.3	-10.9	16.4	254.79	0	0.509
2007 12 7	1e2	APO	3 33 5.94	-13.9	-3.7	0.8	0.5	2.1	-10.0	14.4	254.76	0	0.750
2007 12 7	1e2	MON	3 33 21.46	-25.6	-6.9	2.5	2.5	-8.2	-18.2	26.6	254.75	0	0.810
2007 12 8	2e3	MON	1 58 6.77	40.6	11.0	1.9	2.4	-9.4	-9.5	42.0	74.71	0	0.757
2007 12 8	2e3	VLT	1 58 6.57	41.5	11.3	0.7	0.9	-8.5	-9.2	43.1	74.72	0	0.668
2007 12 15	1e3	HAN	14 4 42.31	50.4	13.6	1.5	2.4	-4.3	-7.6	52.2	74.82	0	0.858
2007 12 17	4e3	HAN	14 20 31.79	-0.6	-0.1	8.0	2.2	2.4	-2.6	0.6	254.66	0	0.512
2008 1 4	1e5	TUB	16 16 54.73	27.9	5.1	1.0	1.3	-6.6	-8.8	28.3	79.53	0	0.893

Emelyanov N. V.: 2009, Mutual occultations and eclipses of the Galilean satellites of Jupiter in 2002-2003: final astrometric results. Monthly Notices of the Royal Astronomical Society, V. 394. Issue 2. P. 1037-1044.

Lainey V.:2008, A new dynamical model for the Uranian satellites. Planetary and Space Science, V. 56. P. 1766-1772.

Karkoschka E.: 2001, Comprehensive Photometry of the Rings and 16 Satellites of Uranus with the Hubble Space Telescope, Icarus, V. 151. P. 51-68.