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Nikolai V. Emelyanov. Mutual occultations and eclipses of the Galilean satellites of Jupiter in 2002-2003: final astrometric results. Monthly Notices of the Royal Astronomical Society, 2009, 394, pp.1037-1044. 10.1111/j.1365-2966.2009.14398.x . hal-03732420

HAL Id: hal-03732420
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Submitted on 20 Oct 2022

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Mon. Not. R. Astron. Soc. **394,** 1037–1044 (2009) doi:10.1111/j.1365-2966.2009.14398.x

Mutual occultations and eclipses of the Galilean satellites of Jupiter in 2002–2003: final astrometric results

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Accepted 2008 December 12. Received 2008 December 5; in original form 2008 September 24

ABSTRACT

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.

This work focuses on processing the complete data base of photometric observations of the mutual occultations and eclipses of the Galilean satellites made during the international campaign in 2002–2003. The final goal is to derive new accurate astrometric data.

We propose the most accurate photometric model of mutual events based on all the data available to date about the satellites, and develop the corresponding method for extracting astrometric data. This method is applied to derive astrometric data from photometric observations of mutual occultations and eclipses of the Galilean satellites.

We process the 371 light curves obtained during the international campaign of photometric observations of the Galilean satellites in 2002–2003. As compared with the theory, the rms 'O-C' residuals with respect to theory is equal to 0.055 and 0.064 arcsec in right ascension and declination, respectively, for the 274 best observations. Topocentric or heliocentric angular differences for satellite pairs are obtained for 119 time instants during the time period from 2002 October 10 to 2003 July 17.

Key words: eclipses – occultations – planets and satellites: individual: Galilean satellites of Jupiter.

1 INTRODUCTION

Photometric observations of mutual occultations and eclipses of natural satellites of planets offer an efficient source of new astrometric data. These data are being used for further improvement of the dynamical models of the motion of planets and satellites and their ephemerides. Mutual events of natural satellites have been observed extensively since 1973 (Brinkmann & Millis 1973; Arlot, Camichel & Link 1974). The characteristics of such phenomena and the results of observations are described in many publications (see e.g. Arlot et al. 1982, 1992, 1997; Emelianov et al. 2000; Arlot et al. 2006). Astrometric reduction of these observations was performed by a number of authors (Aksnes & Franklin 1976; Aksnes et al. 1984; Vasundhara 1991; Emelianov et al. 2000; Vasundhara 2002; Vasundhara et al. 2003).

Mutual occultations and eclipses of the Galilean satellites of Jupiter occur every 6 years for about 9 months. Given that each event lasts only a few minutes, only 30 per cent of all such phenomena can be observed at a given observatory, implying a need for international campaigns of photometric observations.

In 2002–2003, the Institut de Mécanique Céleste et de calcul des éphémérides (IMCCE), France, organized and coordinated an international campaign to observe the mutual occultations and eclipses of the Galilean satellites (Arlot 2002). Within the framework of this campaign, many results of the photometric observations made on the different observatories have been collected (Arlot et al. 2009) and stored in a common data base. The data are available online at ftp://ftp.imcce.fr/pub/NSDC/jupiter/raw_data/phenomena/mutual/2003. These results become useful when astrometric data are derived from all photometric observations via an advanced method incorporating light scattering laws, the theory of the motion of planets and satellites and the data on the physical properties of satellite surfaces.

Emelyanov & Gilbert (2006) and Emelyanov (2008) made preliminary attempts to reduce the results of photometric observations of the Gallilean satellites during their mutual occultations and eclipses in 2002–2003. An extensive analysis performed in the above papers leads us to conclude that systematic errors must be

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due to incorrect background subtraction from photometric counts. In the case of mutual occultations, the flux drop depends on the ratio of the mean albedos of two satellites. Adopting a wrong satellite albedo leads to systematic errors in the derived satellite coordinates.

In this paper, we report the final astrometric results derived by applying our original method (Emelyanov 2000, 2003) to all photometric observations of the Galilean satellites made during the international campaign PHEMU-2003.

2 RESULTS OF PHOTOMETRIC OBSERVATIONS

Many mutual events involving the Galilean satellites of Jupiter have been observed in 2002–2003. The results of photometric observations during the mutual occultations and eclipses of these satellites performed at various observatories worldwide were collected at the IMCCE. The entire data base includes 391 light curves of satellites. However, 20 observations proved to be unsuccessful. In order to facilitate the use of the data, the latter were converted into a common format as magnitude drop versus time (UTC scale). Thus, a total of 371 light curves were obtained during the international campaign of photometric observations of the Galilean satellites in 2002–2003, which are available online (see the address given above). These satellite light curves are inferred from observations made at 45 observatories worldwide. We thus have photometric data for 119 mutual events. A total of one to 24 events were observed at each observatory. Only 24 events were simultaneously observed from at least five observatories. For our reduction we prefer to use the data directly received by the IMCCE from the observers and made available to the author of this paper.

Table 1 presents the sites of observation and the number of light curves deduced from photometric measurements for each site. The table needs a few comments. Two groups of observers worked independently at the observatory in Pulkovo with two different telescopes: one directed by Dr T. P. Kisseleva ('Pulkovo K') and another one directed by Dr A. V. Devyatkin ('Pulkovo D'). At the time of observations, Terskol Observatory belonged to Ukraine but it is located on the territory of Russia. Dushak-Erekdag Observatory is located on the territory of Turkmenistan, but is operated by the Odessa State University (Ukraine). The MPC codes of some observatories are given in the brackets. The catalogue of the light curves made by the observers of the international campaign in 2002–2003 is published by Arlot et al. (2009). Note that 14 more observations were received by IMCCE and are included in our analysis, but only six of them proved to be successful.

The observers record their initial data in two-column files. The columns give the time of the photometric measurement and the measured flux of light from the satellites. In the case of a mutual occultation, the total flux from both satellites is always measured. During a mutual eclipse, only the measurements of the flux from the eclipsed satellite are available; however, in some cases the observers measured the total flux from the eclipsed and eclipsing satellites. The reduction of observations depends on the composition of the initial data (i.e. whether we deal with the flux from the eclipsed satellite or with the total flux from both satellites). Unfortunately, some observers failed to indicate in their results the satellites whose flux they have measured. The initial data also include the indication of the filter employed. The reduction procedure also allows us take into account the coordinates of observatory. Time is on the UTC scale.

3 EXTRACTION OF ASTROMETRIC DATA FROM THE PHOTOMETRY OF SATELLITES

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. See Emelyanov (2000, 2003) for a description of the method, which we have already used in our earlier works (Emelianov et al. 1999, 2000; Emelyanov & Gilbert 2006).

In our method, we test two light scattering laws – the Lommel–Seeliger and Hapke laws – among the great variety of those considered in planetology. Hapke (1981, 1984) analyzed the most detailed and general law of scattering by the surface of a celestial body. His scattering function depends on five parameters, which are constant for a given satellite and spectral band. We found only two complete sets of published Hapke parameters for the Galilean satellites. McEwen, Johnson & Matson (1988) give the Hapke parameters for the rough surface of the *Io* satellite, whereas Domingue & Verbiscer (1997) refined the Hapke function for rough surfaces and, in particular, for the other tree Galilean satellites. The scattering function includes a number of empiric relations.

We adopt Hapke's scattering law in our final solution. Given that most of the observations of the Galilean satellites were made with the *V* filter, or with no filter at all, we use the three-parameter function (3P-HG) and adopt the set of parameters from Domingue & Verbiscer (1997) for the 0.55 μm spectral band. During the event, almost half of the leading and half of the trailing hemisphere of each satellite were viewed from the Earth, and we therefore use the mean values for the corresponding parameters.

A few observations were made with the *R* filter for which no Hapke parameter values were available, and we therefore attempted to correct the albedo ratio of the two satellites using the relations from Morrison & Morrison (1977). However, this had only a minor effect on the inferred satellite coordinates compared to observational errors.

Observations at Ukkel observatory were made with an 892 μm filter, and we therefore reduced them introducing extra cofactors to the satellite albedo ratios with wavelength dependence of albedo adopted from Morrison & Morrison (1977). In particular, we adopt the cofactors of $M(p_1/p_3) = 1.08$, and $M(p_3/p_2) = 0.918$, where p_1, p_2, p_3 are the albedos of *Io*, *Europa* and *Ganymede*, respectively.

We allow for solar limb darkening as described by Emelyanov (2003) and Emelyanov & Gilbert (2006), and use tables from Makarova et al. (1998) to this end.

To allow for irregularities of the satellite surface in our photometric model of mutual occultations and eclipses, we tried to use the maps of the Galilean satellites of Jupiter as described by Emelyanov & Gilbert (2006). The analysis performed in the above paper shows that the use of published maps of the Galilean satellites is of doubtful value in our case because of the discrepancy between these data and ground-based photometry of the satellites made at different rotation angles.

In our final solution, we use the dependence of the magnitudes of the Galilean satellites on angle of rotation. This dependence is based on single-band (*V*) ground-based photometry by Morrison & Morrison (1977).

To explain the main idea of our method, let us introduce Cartesian coordinate system *X*, *Y*, *Z* with the origin at the centre of the occulted or eclipsed satellite. We choose the direction of

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Table 1. List of the observatories and number of observations. Column X gives the number of observations used to derive the coordinates $X(t^*)$, $Y(t^*)$ (P observations of X show big O-C residuals because of poor results, B observations of X show big O-C residuals because of faulty background subtraction); Column C the number of event observations that yielded only the position angle; Column L the number of observations that yielded only the position angle because of poor results and Column U the number of unused observations (i.e. unsuccessful observations or those lacking proper explanation or with no event observed). Thus, the number of observations received from an observatory is equal to X+C+L+U.

Code	Conventional name of of observatory	Country	Receptor	X (P,B)	C,L	U	Longitude, hours to the West	Latitude, degrees to the North
ANT	Antony	France	CCD	3 (1,-)	-, -	-	−0.152222	48.45000
ARM	Armagh (981)	N. Ireland	CCD	12 (1,1)	-, 1	1	−0.443315	54.35306
BOR	Bordeaux (999)	France	CCD	11	-, -	-	0.351667	44.83528
BRE	Brescia	Italy	Visual	1	-, 5	-	−0.681111	45.55000
BUC	Bucharest (073)	Romania	Photometer	5	-, -	-	−1.739722	44.41389
CAN	Sabadell	Spain	CCD	15 (1,4)	-, 1	1	1.105556	28.25000
CAT	Catania (156)	Italy	Photometer	13 (-,1)	2, -	-	−1.005722	37.50367
CHA	Chateaugiron	France	CCD	8 (1,1)	2, -	-	1.500336	48.04460
CHE	Chemnitz	Germany	Visual	2 (2,-)	-, -	-	−0.856852	50.82361
CLU	Cluj-Napoca	Romania	CCD	14 (-,3)	2, -	-	−1.573194	46.71333
CRI	Nauchny (095)	Russia	Photometer	14 (-,2)	-, -	-	−2.267778	44.72694
DAX	Dax (958)	France	CCD	1	-, -	-	−0.068574	43.69306
DOL	Dolberg	Germany	TV	1 (-,1)	-, -	-	−1.739722	44.41389
ELG	Elgin	USA	CCD	1	-, -	-	7.861093	45.57389
GIE	Gieres	France	CCD	2	-, 1	-	−0.382222	45.18334
KAZ	Alma-Ata (210)	Kazakstan	CCD	7 (-,1)	2, -	1	−5.130278	43.18611
KIS	Pulkovo K (084)	Russia	CCD	15 (2,2)	-, -	-	−2.021222	59.76750
KOU	Kourovka (168)	Russia	Photometer	3 (1,-)	-, -	-	−3.866667	56.80000
LAN	Lanester	France	CCD	1	-, -	-	0.223611	47.75000
LIL	Lille	France	CCD	12	-, 1	-	−0.204722	50.61583
LUM	Lumezzane (130)	Italy	Photometer	4 (3,-)	1, -	1	−0.682713	45.66636
MAS	Massa	Italy	CCD	-	-, 1	-	−0.673537	44.04194
MAY	Mainz (090)	Germany	CCD	1	-, -	-	−0.549923	49.91820
MEU	Meudon (005)	France	TV	10 (-,3)	-, -	1	−0.148750	48.80500
MNG	Monegrillo	Spain	CCD	6	-, -	-	−0.027463	41.64389
MON	Monterrey	Mexico	Video	9 (2,-)	-, 1	-	6.691594	25.64341
NOV	Novara	Italy	Visual	-	-, 2	2	−0.575000	45.47500
NYR	Nyrola (174)	Finland	CCD	14	-, -	-	−1.700870	62.34222
ODE	Dushak-Erekdag	Ukraine	Photometer	6 (2,3)	-, -	1	−3.858889	37.92417
OHP	Haute-Provence (511)	France	CCD	20 (2,7)	2, 3	2	−0.381111	43.92933
PAL	La Palma (950)	Spain	CCD	24 (-,4)	-, -	-	1.192111	28.76000
PEN	Yunnan (286)	China	CCD	7	-, -	-	−6.852550	25.02932
POR	Tomar	Portugal	CCD	-	-, 1	-	0.608548	38.72500
PRA	Prague (541)	Czech Rep.	CCD	3	-, -	-	−0.961111	50.08333
PUL	Pulkovo D (084)	Russia	CCD	17 (-,1)	-, -	2	−2.021222	59.76750
ROZ	Rozhen (071)	Bulgaria	Photometer	5 (2,1)	-, -	-	−1.649444	41.69305
SAR	Torrecilla	Spain	CCD	9	-, -	-	0.057018	41.50194
SEN	Sendai (893)	Japan	Photometer	5 (1,-)	-, -	2	−9.391666	38.27666
SOB	Sobota	Slovakia	CCD	4 (1,-)	-, -	1	−1.333778	48.37444
STR	Strasbourg (522)	France	CCD	2 (1,1)	-, -	-	−0.518000	48.58333
TER	Terskol (B18)	Ukraine	CCD	12 (1,-)	-, -	-	−2.833389	43.27480
UKK	Ukkel	Belgium	CCD	11 (-,1)	1, -	1	0.290537	50.79861
VBO	Kavalur (220)	India	CCD	16 (1,1)	-, -	-	−5.254811	12.57733
VIL	Mundolsheim	France	CCD	13 (1,1)	-, -	2	−0.514259	48.64722
VOL	Vienna	Austria	Visual	1 (1,-)	-, 2	2	−1.093333	48.20000
	45 observatories		Total:	340 (27,39)	12, 19	20		

the Z-axis to coincide with the topocentric direction of the occulted satellite or with the heliocentric direction of the eclipsed satellite. The X-axis is parallel to the plane of the Earth equator. Let the Y-axis always make an acute angle with the Earth axis and complement the X- and Z-axes to a right-handed coordinate system. In this case, the direction of the X-axis is unambiguously determined as the Z-axis is not parallel to the Earth axis in all cases of ground-based observations of natural satellites.

The measured flux $E(t)$ during an event at time t can be expressed as

$$E(t) = K\,S(X(t),\ Y(t)) + P, \tag{1}$$

where $X(t)$ and $Y(t)$ are the coordinates of the topocentric projection of the occulting satellite on to the X, Y plane. In the case of a mutual eclipse, $X(t)$ and $Y(t)$ are the coordinates of the heliocentric projection of the eclipsing satellite.

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The function $S(x, y)$ describes the model of the phenomenon. We assume that $S(x, y) = 1$ outside the event. The parameter K is a scalefactor for the flux drop during the event, and it is equal to the total flux measured outside the event. We refer to the part of the photometric count that is not due to the satellite flux as the background and denote it as P.

Theories of the motion of planets and satellites can be used to compute the theoretical values of functions $X(t)$, $Y(t)$, i.e. $X_{\rm th}(t_i)$, $Y_{\rm th}(t_i)$ at times t_i $(i = 1, 2, \ldots, m)$ for each photometric measurement. Here, m is the number of photometric counts during a single event. The actual values of $X(t_i)$, $Y(t_i)$ differ from $X_{\rm th}(t_i)$, $Y_{\rm th}(t_i)$ by the corrections D_x, D_y.

Our method consists in solving conditional equation

$$E_i = K\ S(X_{\rm th}(t_i) + D_x,\ Y_{\rm th}(t_i) + D_y) + P \qquad (i = 1, 2, \ldots, m) \tag{2}$$

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

In our final solution, we use the theory of the motion of the Galilean satellites developed by Lainey, Arlot & Vienne (2005) to compute the theoretical values $X_{\rm th}(t_i)$, $Y_{\rm th}(t_i)$ and corrections D_x, D_y.

Astrometric result of the observation may have the form of any corrected relative position of satellites $X(t^*) = X_{\rm th}(t^*) + D_x$, $Y(t^*) = Y_{\rm th}(t^*) + D_y$ 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.

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, and α_p, δ_p are the corresponding coordinates of the occulted or eclipsed satellite. In the cases of mutual eclipses, these coordinates are heliocentric.

Given the topocentric or heliocentric distances R of the satellites, one can compute X'', Y'' from X, Y using precise equations. In the cases of ground-based observations of the mutual events of natural satellites, approximate relations

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

could be used, which are accurate for these observations to 0.00001 arcsec.

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

In the case where the same event was observed at two observatories, the time instants t^* may differ because of observational errors, and hence the differences between the coordinates $X(t^*)$, $Y(t^*)$ obtained at two observatories cannot be viewed as bias indicators.

The quantities D''_x, D''_y characterize the agreement between theory and observations. These quantities can be used to compare the results of observations made at different observatories.

The errors σ_x and σ_y of the derived parameters $X''(t^*)$, $Y''(t^*)$ characterize the internal accuracy of photometry estimated via the least-square method.

After computing the D_x, D_y values, we determine the minimum value $S_{\rm min}$ of the normalized flux $S(X_{\rm th}(t) + D_x,\ Y_{\rm th}(t) + D_y)$ based on observations. The maximum flux drop during the event is then equal to $1 - S_{\rm min}$.

In certain cases, where the corrections D_x, D_y could not be reliably determined, we convert the coordinates X, Y into the coordinates connected with the apparent trajectory of the relative satellite motion. Once determined in this coordinate system, the corrections were converted into the D_x, D_y values.

The occulting satellite may pass above or below the occulted satellite at the same distance from the latter producing the same dips in the total flux. Thus, any observed light curve of the satellites has two solutions for the corresponding coordinate differences of apparent coordinates of satellites. For each observation the minimum values of D_x, D_y was a factor taken into account when choosing between the two solutions.

Most of our astrometric results come from processing the mutual event observations where both corrections D_x, D_y could be obtained.

In the case where the apparent disc of one of the satellites overlaps fully with that of the other satellite, the solution becomes uncertain in one of the relative coordinates. Similar effects also occur in the case of mutual eclipses of satellites. In such cases, observations yield only the correction to the position of satellite along the trajectory of its relative motion. As a result, only position angle A can be determined for a certain time instant (t^*) near the time of minimum apparent distance between the satellites. The data obtained in such cases form a separate section of our astrometric results.

In our final solution for astrometric coordinates, we assume that the effect of the background on the result of photometric measurements is already eliminated by the observers, and therefore we set $P = 0$.

4 COMPARISON OF THE RESULTS OBTAINED WITH TWO LIGHT SCATTERING LAWS AND TWO METHODS TO ALLOW FOR SATELLITE ROTATION

Although we use the Hapke scattering law and the dependence of the magnitudes of the Galilean satellites on angle of rotation in our final solution, we nevertheless also tried to use other methods as well.

The irregularity of the reflective properties of the satellite surface affects the astrometric data derived from photometry of satellites during their mutual phenomena in two different ways. If only the flux of the eclipsed satellite is measured, the irregularities of the satellite disc with the fixed angle of rotation must be taken into account. These variations have only a minor effect on astrometric results. Our estimates and the estimates of Vasundhara et al. (2003) show that the errors introduced by neglecting such variations do not exceed 0.01 arcsec in the apparent relative positions of the Galilean satellites of Jupiter.

The effect of a variation of the reflecting properties over the entire surface shows up in the cases where the sum of the fluxes from two satellites is measured during the phenomenon. In such cases, astrometric results depend substantially on the albedo ratio of two satellites. The albedo averaged over the visible disc is different for different angles of satellite rotation. These variations may be as high as 10–15 per cent for the Galilean satellites of Jupiter. The errors of the astrometric results obtained can be as high as 0.2 arcsec if the variations of the satellite albedo are not taken into account.

In order to estimate the differences between the satellite coordinates computed using different methods, we reduced a group of selected observations and confronted the results to those obtained with the finally adopted method.

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Table 2. Results of the estimations of accuracy for three variants of data reduction for 104 selected flux curves of the Galilean satellites.

Method	Total random errors in X'' (arcsec)	Total random errors in Y'' (arcsec)	Total rms of O-C in X'' (arcsec)	Total rms of O-C in Y'' (arcsec)
Hapke law, rotation var.	0.0327	0.0283	0.0733	0.1203
Lommel–Seeliger law, rotation var.	0.0328	0.0271	0.0735	0.1212
Hapke law, maps	0.0328	0.0268	0.0777	0.1277

In the second version, we allowed for the variations in the mean albedo of the satellite disc as a function of the angle of rotation as above, but used the Lommel–Seeliger law instead of the Hapke scattering law. In the third version, we use the Hapke scattering law, while using satellite maps to allow for satellite surface irregularities. For this analysis, we used about 104 satellite flux curves measured during the mutual osculation.

We use the rms value of all the rms relative satellite coordinates derived from each curve (total random errors) as a criterion of the accuracy of the results obtained. Our second criterion involves computing the rms values of the deviations of the inferred coordinates from their ephemeris values (total rms of 'O-C'). Table 2 gives the results of assessing the accuracy of three variants of reduction of observations considered in this paper. As is evident from this table, all three versions yield approximately the same astrometric accuracies.

5 ATTEMPTS AT THE CORRECTION OF THE BACKGROUND LEVEL IN THE RESULTS OF PHOTOMETRIC OBSERVATIONS AND REFINING THE SATELLITE ALBEDOS OF THE SATELLITES

In our solution for astrometric coordinates, we assume the results of photometric measurements have been completely corrected for the effect of background and set the parameter P equal to zero. In the case of incorrect background subtraction, this parameter actually differs from zero and systematic error appears in the parameter D_y. Our analysis (Emelyanov 2008) shows that joint least-square determination of four parameters, D_x, D_y, K and P, may result in highly correlated parameter errors.

We nevertheless tried to refine parameter P using observational data. Let us consider an example. The observations of the eclipse of *Ganymede* by *Callisto* on 2003 February 18 were made at six observatories. We performed two astrometric reductions of these observations. One of them involved the refinement of four parameters D_x, D_y, K,, P. In the other reduction, we set parameter P equal to zero. We compare the results of these two reductions in Fig. 1. Treating parameter P (background) as an unknown parameter leads to even larger systematic errors in the astrometric results. Several examples confirm that the fit of parameter P is unreliable.

As we show in another paper (Emelyanov 2008), errors in the adopted satellite albedos translate into significant errors in the astrometric results obtained. The solution proposed by Vasundhara et al. (2003) was to treat the albedo ratio P_p/P_a of the two satellites as an unknown parameter. We too tried to refine the albedo ratio from observations by adding parameter M to the list of fitted parameters:

$$r = \frac{P_p}{P_a} M.$$

Here, r is the adopted albedo ratio of the two satellites, and P_p and P_a are the given albedos of the occulted and occulting satellites, respectively. Table 3 gives an example of our results. One can see

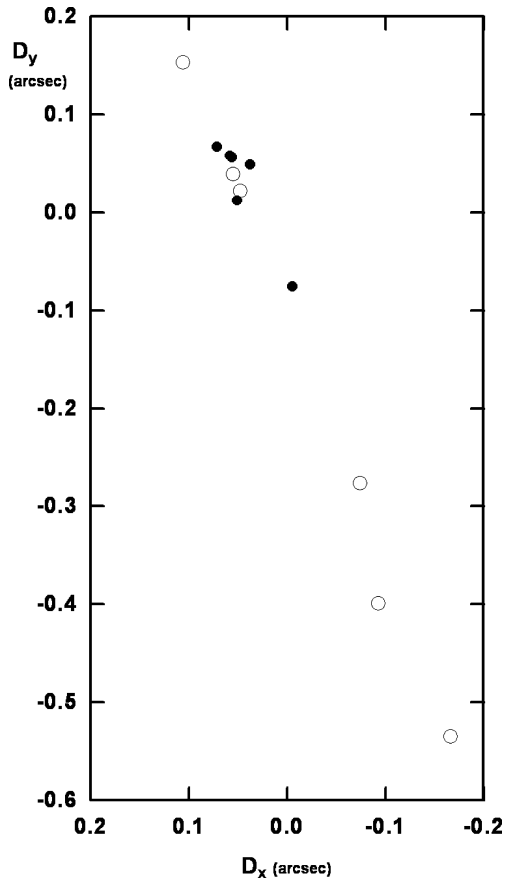

Figure 1. Astrometric results inferred from the photometry made during the eclipse of *Ganymede* by *Callisto* on 2003 February 18. The filled and open circles show the results obtained with $P = 0$ and with background parameter P treated as a fitted quantity, respectively.

Table 3. Results of the fit of the parameters to the photometric observations including an extra multiplier to the albedo ratio. The extra multiplier applies to the *Io* to the *Callisto* albedo ratio for the first event and to the inverse ratio for all other events.

Event	Observatory code	Extra albedo multiplier M_r ($r = P_p/P_a M_r$)
2003-02-19-4o1	LIL	1.44 ± 1.11
2003-02-27-1o4	CLU	1.21 ± 0.30
2003-02-27-1o4	ROZ	0.90 ± 0.07
2003-02-27-1o4	MNG	1.42 ± 0.51
2003-02-28-1o4	CLU	0.87 ± 0.25
2003-02-28-1o4	SAR	1.26 ± 0.33

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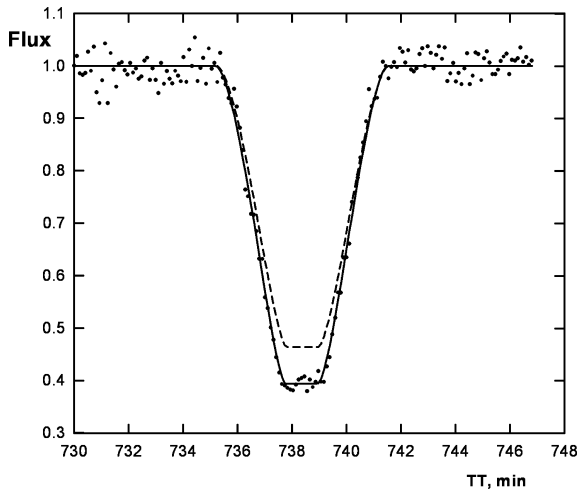

Figure 2. Comparison of the results of the photometric observations (the filled circles) made at Yunnan observatory during the occultation *Europa* by *Callisto* on 2003 February 20 with the theoretical light curve computed with the albedo of *Callisto* multiplied by a factor of 0.74 (the solid line) and without this correction (the dashed line).

that observations at different observatories yield very different values for parameter M for the same pair of satellites (*Io*, *Callisto*). It is clear that the fitted parameter M absorbs the uncertainty in the background measurements. On the other hand, this uncertainty can be directly resolved by refining the parameter P as we show above.

The results of our attempts to refine parameters P, M proved to be unreliable, and we finally decided to set $P = 0$, $M = 1$ and treat the systematic errors of each observation as random errors on a large series of observations

Total mutual occultations require a special discussion. During a total mutual occultation, the visible disc of one satellite occults completely the disc of the other satellite. The total flux of both satellites does not depend on the mutual position of satellites, but it depends substantially on their albedo ratio. The measured flux drop may not coincide with its computed value because of two factors: (1) incorrectly adopted albedo ratio of the two satellites and (2) incorrect background subtraction. Fig. 2 illustrates the results of the reduction of observations of a total mutual occultation. The light curve computed using the Hapke parameters adopted from Domingue & Verbiscer (1997) does not agree with the results of observations. The agreement can be achieved by introducing the 0.74 multiplier to the albedo of *Callisto* or by replacing the coefficient values $K = 1$, $P = 0$ by $K = 1.13$, $P = -0.13$. We discuss similar cases in another paper (Emelyanov 2008). An analysis of several observations of mutual occultations involving *Callisto* leads us to conclude that the actual albedo of this satellite must be decreased by a factor of 1.36 compared to the data reported by Domingue & Verbiscer (1997). We use this multiplier when deriving astrometric data.

6 ASTROMETRIC RESULTS

We subdivide our final astrometric results into two sections. The first section includes the results obtained from the observations where two coordinates, $X''(t^*)$ and $Y''(t^*)$, 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 and 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 arcsec) and position angle A (in degrees) corresponding to $X''(t^*)$, $Y''(t^*)$. We also give the minimum level $S_{\min}$ of normalized flux. We assign flag Q to each observation in order to indicate the quality and the reliability of the result. Flag Q may have acquired one of the following tree values: '0' for normally determined coordinates; '1' for the cases where the result of the observations at the given observatory differs considerably from the results of other observatories and '2' for the results obtained from poor photometric data.

Right ascensions and declinations are measured in the ICRF. All angular quantities are in arcsec. In the case of a mutual occultation, t^* is the time of topocentric observation of satellites. In the case of a mutual eclipse, t^* is the time of topocentric observation of the eclipsed satellite.

The σ_x and σ_y quantities can be interpreted as internal errors of $\Delta\alpha \cos\delta_p$ and $\Delta\delta$, respectively, and D''_x, D''_y are the residuals with respect to the theory of Lainey et al. (2005).

Table 4 gives a fragment of the first section of astrometric results.

The data in the second section consist 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 arcsec. Also, a sign R is assigned showing the reason why only one coordinate was determined: '0' for a total mutual eclipse or occultation observed, '1' for the results obtained from poor photometric data. In these cases, the apparent relative position of the satellite measured across the apparent trajectory cannot be determined accurately enough, and therefore position angles can be determined only up to $\pm 180°$($A \pm 180°$).

Table 5 gives a fragment of the second section of the astrometric results.

Tables 4 and 5 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.

7 ESTIMATION OF THE ACCURACY OF THE DERIVED ASTROMETRIC RESULTS

We use the following estimates to assess the astrometric results obtained. 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. In Table 6, the rms values of these estimates for all the light curves reduced to determine two coordinates $X''(t^*)$, $Y''(t^*)$ are listed as total random errors.

We also compute the mean values of D''_x, D''_y designated as $\overline{D''_x}$, $\overline{D''_y}$ for each event observed simultaneously at N ($N > 1$) observatories and determine the differences $D''_x - \overline{D''_x}$, $D''_y - \overline{D''_y}$ for each observatory and event. We finally compute the rms of all these differences over all events and all observatories. We treat these residuals as

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Table 4. Fragment of the first section of astrometric results. The full table is available in the online version of the article (see Supporting Information).

Date (y-m-d)	Type	Obs code	Time (h, m, s, UTC)	$X''(t^*)$ (arcsec)	$Y''(t^*)$ (arcsec)	σ_x (arcsec)	σ_y (arcsec)	D''_x (arcsec)	D''_y (arcsec)	s (arcsec)	A (○)	Q	$S_{\min}$
2002-10-28	2o1	PUL	1 10 56.0	−0.017	−0.048	0.045	0.103	−0.008	0.070	0.051	199.22	0	0.580
2002-11-11	2o1	CHA	5 52 2.9	0.100	0.280	0.023	0.023	0.273	−0.080	0.298	19.60	0	0.720
2002-11-12	4o2	CLU	23 8 19.5	−0.182	−0.516	0.015	0.011	0.001	0.059	0.547	199.41	0	0.665
2002-11-18	2e1	PAL	6 4 39.8	−0.220	−0.738	0.052	0.024	−0.097	0.035	0.770	196.58	0	0.953
...													
2003-3-25	1e3	BOR	20 8 26.8	−0.269	−0.748	0.009	0.005	−0.028	0.062	0.795	199.75	0	0.869
2003-3-25	1e3	CAT	20 8 52.4	−0.274	−0.764	0.043	0.023	0.044	0.019	0.812	199.75	0	0.878
2003-3-25	1e3	CRI	20 8 26.8	−0.266	−0.741	0.006	0.003	−0.023	0.070	0.787	199.75	0	0.924
2003-3-25	1e3	LIL	20 8 26.3	−0.288	−0.802	0.043	0.022	−0.048	0.009	0.852	199.75	0	0.898
2003-3-25	1e3	MEU	20 8 33.7	−0.269	−0.749	0.024	0.013	−0.005	0.054	0.796	199.75	0	0.869
2003-3-25	1e3	NYR	20 8 29.2	−0.273	−0.760	0.015	0.008	−0.023	0.048	0.808	199.75	0	0.930
2003-3-25	1e3	OHP	20 8 7.7	−0.191	−0.532	0.024	0.018	−0.006	0.300	0.565	199.75	1	0.848
2003-3-25	1e3	PUL	20 8 32.4	−0.272	−0.759	0.021	0.011	−0.013	0.046	0.806	199.75	0	0.930
2003-3-25	1e3	SAR	20 8 26.6	−0.287	−0.800	0.019	0.010	−0.045	0.011	0.850	199.75	0	0.942
...													
2003-6-17	4o2	ODE	16 11 49.0	0.263	0.767	0.016	0.006	0.134	0.103	0.811	18.92	2	0.958
2003-7-7	2o1	ODE	16 9 1.7	0.218	0.594	0.013	0.006	0.769	0.319	0.633	20.11	2	0.964
2003-7-17	1o3	ODE	16 12 0.6	0.098	0.258	0.012	0.016	0.217	0.096	0.276	20.77	2	0.754

Table 5. Fragment of the second section of astrometric results. The full table is available in the online version of the article (see Supporting Information).

Date (y, m, d)	Type	Obs code	Time (h, m, s, UTC)	A (○)	σ_{along} (arcsec)	R
2002-12-5	2e1	OHP	23 57 45.5	17.11	0.016	1
2002-12-16	4o1	CLU	2 10 18.2	199.84	0.003	0
2002-12-16	4o1	OHP	2 10 21.8	199.67	0.018	0
...						
2003-5-4	2e1	CAT	21 8 21.64	20.41	0.014	0
2003-5-21	1e3	NOV	19 34 2.78	20.97	0.047	1
2003-5-24	3e1	VOL	20 51 51.92	20.81	0.030	1

Table 6. Estimates of the accuracy of the results of astrometric reduction performed to determine two coordinates $X''(t^*)$, $Y''(t^*)$.

Type of total error estimates	All 340 observations X'' (arcsec)	All 340 observations Y'' (arcsec)	Only 274 normal observations ($Q = 0$) X'' (arcsec)	Only 274 normal observations ($Q = 0$) Y'' (arcsec)
Random	0.036	0.029	0.029	0.021
Systematic	0.079	0.091	0.047	0.044
Rms of O-C	0.107	0.131	0.055	0.064

systematic errors due to background subtraction errors in the photometric results and to the use of incorrect satellite albedos in the reduction of observations of mutual occultations. We list these estimates in Table 6 as total systematic errors.

The corrections D''_x and D''_y remain constant during the event and characterize the discrepancy between the theory and observations. The corresponding quantities derived from observations made at different observatories can be compared to each other. The resulting discrepancies are due to observational biases.

In Table 6, total rms of O-C is the total rms of all D''_x and D''_y computed over all events, and all observatories for the cases were two coordinates $X''(t^*)$, $Y''(t^*)$ were determined.

8 CONCLUSIONS

We reduce the entire data base of photometric observations of the mutual occultations and eclipses of the Galilean satellites made during the international campaign in 2002–2003 to determine the topocentric or heliocentric angular differences for satellite pairs at 119 time instants during the time interval from 2002 October 10 to 2003 July 17. The standard errors of the relative satellite coordinates due to the random errors of the photometry are equal to 0.029 and 0.021 arcsec in right ascension and declination, respectively, for successful observations. The rms 'O-C' residuals with respect to the theory by Lainey et al. (2005) are equal to 0.055 and 0.064 arcsec in right ascension and declination, respectively, for successful observations.

The currently best photometric model for the reduction of photometric observations of the mutual occultations and eclipses of the Galilean satellites incorporates the following effects: the Hapke scattering law with the parameters published to date; solar limb darkening; uniform reflective properties of the visible satellite surface for a given angle of rotation and variations of albedo with the angle of rotation.

Systematic errors of the photometry of mutual occultations and eclipses of satellites are most likely due to incorrect background subtraction from photometric counts.

An examination of several observations of mutual occultations involving the *Callisto* satellite made at different observatories leads us to conclude that the real albedo of this satellite must be decreased by a factor of 1.36 compared to the data from Domingue & Verbiscer (1997).

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research, project no. 07-02-92169-CNRS-a, and the 'Programme International de Cooperation Scientifique' no. 3840 of CNRS.

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SUPPORTING INFORMATION

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

Table 4. The first section of astrometric results.
Table 5. The second section of astrometric results.

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