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The PHEMU03 catalogue of observations of the mutual phenomena of the Galilean satellites of Jupiter*

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ABSTRACT

Context. In 2003, the Sun and the Earth passed through both the equatorial plane of Jupiter and therefore the orbital planes of its main satellites.
Aims. During this period, mutual eclipses and occultations were observed and we present the data collected.
Methods. Light curves of mutual eclipses and occultations were recorded by the observers of the international campaign PHEMU03 organized by the Institut de mécanique céleste, Paris, France.
Results. We completed 377 observations of 118 mutual events from 42 sites and the corresponding data are presented in this paper. For each observation, information about the telescope, receptor, site, and observational conditions are provided.
Conclusions. This paper gathers all data and indicates a first estimate of its precision. This catalogue of these rare events should constitute an improved basis for accurate astrometric data useful in the development of dynamical models.

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

1. Introduction

Observations of natural satellite mutual events have been performed intensively since 1973 and have proved to be a very accurate way to get astrometric measurements of the natural satellites. In 2003, we encouraged observers to complete as many observations as possible by organizing and coordinating an international campaign to monitor these rare events. This campaign named PHEMU03 allowed us to collect 377 light curves of 118 mutual events studied by the observers of our international network consisting of 42 sites.

In this paper, we provide all data collected by our network. We note that 19 more observations were completed (at Meudon, Pulkovo, Armagh, Nauchny, Novara, Sendai, Terskol, and Sobota), but due to adverse meteorological conditions or hardware problems, no reliable information could be derived from the light curves, which are not included in this paper. Another paper (Emelianov 2008) will provide the astrometric data extracted from the light curves by a sophisticated photometric model of the light curves. In this paper, we aim to provide the photometric data and observational parameters useful to future work on the improvement of dynamical models and models of satellite surfaces. These data are available through the data center NSDC dedicated to the natural satellites[1].

2. The mutual events

The Earth and the Sun traverse the equatorial plane of Jupiter every six years. The Jovian declinations of the Earth and the Sun then become zero and, since the orbital plane of the Galilean satellites is close to the equatorial plane of Jupiter, the satellites occult and eclipse each other.

* Table 4 and lightcurves (in ascii format) are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/493/1171

[1] Data center at http://www.imcce.fr/nsdc.

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Table 1. Results of the past campaigns of observations.

	1985	1991	1997	2003
Number of sites	28	56	42	42
Number of light curves	166	374	292	377
Number of observed events	64	111	148	118

The 2003 period was particularly favorable because the equatorial plane crossing occurred during the opposition of Jupiter and the Sun.

Arlot (2002) compiled predictions of all 2003 events using the G5 ephemerides based upon Lieske's theory (Lieske 1977) and the newer L1 ephemerides from Lainey et al. (2004a,b) for the motion of the Galilean satellites. 581 mutual events were computed. Before 2003, several observational campaigns were completed during previous occurrences (Arlot et al. 1997, 2006). Table 1 presents the results derived for each campaign until the present one. Our goal was to observe as many events as possible. Two observations of each event were at least desirable to eliminate any biases in the present observations.

Since no thick atmosphere surrounds any of the Galilean satellites, the photometric observations of these phenomena are extremely accurate for astrometric purposes. The results previously obtained after similar observations of the Galilean satellites, demonstrated that high astrometric accuracy could be achieved: an accuracy of higher than 30 mas was expected (Lainey et al. 2004).

This fact allows us to provide data necessary to improve the theoretical models of the orbital motions and determine the tidal effects in the dynamics of the Galilean satellites.

3. The PHEMU03 campaign

We coordinated an international PHEMU03 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. This is why observers previously involved in PHEMU observational campaigns of mutual events of the Galilean satellites were invited to join the new campaign.

3.1. Receptors

When observing mutual events, only relative photometry can generally be completed. Since the elevation of Jupiter 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 2. Three kinds of receptors were used, the photoelectric photometric single channel receptors, the video cameras, and the two-dimensional CCD receptors. Visual observations are reported only for comparison. The code for the receptors are those provided in the tables for each observation.

3.2. Sites of observation

Coordinated by the IMCCE, this campaign involved the different locations given in Table 3. 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).

Table 2. Receptors used for the observations.

Code as given in the tables	Description
CCT	Intensified camera of T120-OHP
CCD	Unknown
CCD1	CCD SONY ICX021CL
CCD2	Video Watec 902H
CCD3	Video B/W CCD KC381
CCD5	Same as CCT
CCD4	Sony ICX098BQ
CCD6	WebCam Toucam
CCD7	KAF3200E
CCD8	Johnson *I*-type filter
CCD9	ST-6V
CCD10	Hi Sys 22
CCD11	Audine400
CCD12	Sony ICX083AL
CCD13	Sony ICX027BL
CCD14	Camera SBIG ST-8
CCD15	TH7852
CCD16	Imaintel intensified camera
CCD17	Kaf400E with V-Filter
CCD18	TC245-40
CCD19	OS45D
CCD20	Sony ICX 039 BLA (Camera OS45D)
CCD21	Starlight Xpress SX
CCD22	Pictor 416
CCD23	KAF-6300 with filter in Methane band 892 nm +/–20 nm
CCD24	KAF-0400
CCD25	ST7
CCD26	CCD SBIG ST-6
CCD27	Sony HAD ICX38DLA
CCD28	Tektronics CCD
CCD29	CCD Tromsø Univ. (Ostensen, 2002)
VIDEO	Astrovid 2000 video camera With a SONY ICX038 detector chip
WAT	WATEK 902H Camera
PM	Unknown
PM1	EMI-9789QA
PM2	One-channel 1 P21
PM3	Hamamatsu Johnson system V-mag (PCPA-R647-04)
PM4	EMI9502B
PM5	WBVR photometer
PM6	One Channel electro-photometer (Filter *V*)
PMTF	FEU-136 (S-20 (Cs)Na2K Sb photocathode)
NOCT	Nocticon Vidicon camera
VISU	Visual

4. Lightcurves reduction procedure

Light curves were deduced from photometric measurements either with relative photometry performed with photoelectric photometers or with CCD cameras.

Table 3. Sites of observation for the PHEMU03 campaign.

Sites	Telescope	Longitude °	′	″		Latitude °	′	″		Elevation meters
Alma-Ata (Kazakhstan)	T 60	76	57	15	E	43	12	00	N	1450
Antony (France)	T 13	2	17	12	E	48	45	00	N	50
Armagh (Northern Ireland)	T 25	6	38	59	W	54	21	11	N	67
Bordeaux (France)	T 60	0	31	36	W	44	50	06	N	73
Brescia (Italia)	T 20	9	59	30	E	45	26	12	N	94
Bucharest (Romania)	T 15	26	05	48	E	44	24	48	N	267
Catania (Italia)	T 20	15	03	19	E	37	32	54	N	300
Chateaugiron (France)	T 21	1	30	12	W	48	2	41	N	70
Chemnitz (Germany)	L 6	12	51	10	E	50	49	25	N	344
Cluj-Napoca (Romania)	T 41	23	35	37	E	46	42	36	N	750
Dax (France)	T 32	1	01	43	E	43	41	35	N	35
Dolberg (Germany)	T 20	7	54	53	E	51	42	45	N	68
Ekaterinburg (Russia)	T 45	59	30	00	E	56	49	00	N	237
Elgin, Oregon (USA)	T 20	117	55	16	W	45	34	22	N	835
Gieres (France)	T 20	5	44	00	E	45	11	00	N	210
Kavalur-VBO (India)	T 234	78	49	15	E	12	34	38	N	725
Kavalur-VBO (India)	T 102	78	49	15	E	12	34	38	N	725
Lanester (France)	T 20	3	21	15	W	47	45	00	N	0
La Palma (Spain)	T 35	17	53	00	W	28	45	26	N	2300
Lille (France)	L 32	3	4	15	E	50	36	57	N	32
Tomar (Portugal)	T 25	8	23	02	W	39	31	23	N	90
Lumezzane (Italia)	T 40	10	12	27	E	45	39	59	N	830
Massa (Italia)	T 18	10	6	11	E	44	2	31	N	40
Mainz (Germany)	T 25	8	14	56	E	49	55	05	N	205
Meudon (France)	T 100	2	13	54	E	48	48	18	N	162
Monegrillo (Spain)	T 41	0	24	43	E	41	38	38	N	425
Monterrey (Mexico)	T 18	100	22	26	W	25	38	36	N	661
Mt Dushak (Ukraine)	T 80	57	53	00	E	37	55	27	N	2020
Mundolsheim (France)	T 15	7	42	50	E	48	38	50	N	135
Nauchny (Ukraine)	T 60	34	01	00	E	44	43	37	N	600
Novara (Italia)	L 6	8	37	30	E	45	28	30	N	160
Nyrola (Finland)	T 41	25	30	47	E	62	20	32	N	210
OHP (France)	L 15	5	42	36	E	43	53	36	N	665
OHP (France)	T 80	5	42	36	E	43	53	36	N	665
OHP (France)	T 120	5	42	36	E	43	53	36	N	665
Prague (Czech Rep.)	L 18	14	23	52	E	50	04	53	N	327
Prague (Czech Rep.)	T 41	14	23	53	E	50	04	52	N	327
Pulkovo (Russia)	L 65	30	19	30	E	59	46	18	N	75
Pulkovo (Russia)	T 32	30	19	30	E	59	46	18	N	75
Rozhen (Bulgaria)	T 60	24	44	30	E	41	41	35	N	1750
Sabadell (Spain)	T 80	2	05	29	E	41	33	04	N	224
Strasbourg (France)	L 48	7	46	12	E	48	35	00	N	425
Sendai (Japan)	T 36	140	52	30	E	38	16	36	N	55
Sobota (Slovakia)	T 15	20	02	00	E	48	39	00	N	225
Terskol (Russia)	T 60	42	30	03	E	43	16	36	N	3100
Torrecilla de Valmadrid (Spain)	T 20	0	51	19	W	41	30	07	N	382
Ukkel (Belgium)	T 85	4	21	28	E	50	47	51	N	105
Vienna (Austria)	T 10	16	24	00	E	48	12	00	N	190
Yunnan Obs. (China)	T 100	102	47	15	E	25	01	45	N	1940

For observations completed with CCD cameras in video mode, the signal was digitized with digitizing boards. The light curves were also obtained for most of them by aperture photometry. For video observations completed in Meudon or OHP, images were analyzed by completing Gaussian photometry with the AVIA software package (Arlot et al. 1989). 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 (see for example Arlot & Stavinschi 2007).

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 an error time 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.

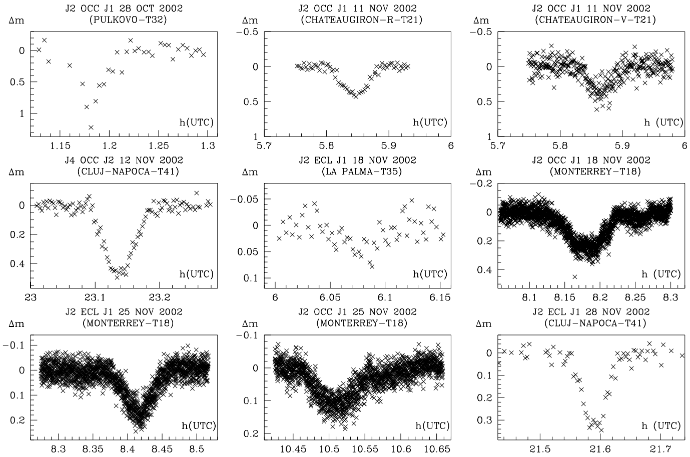
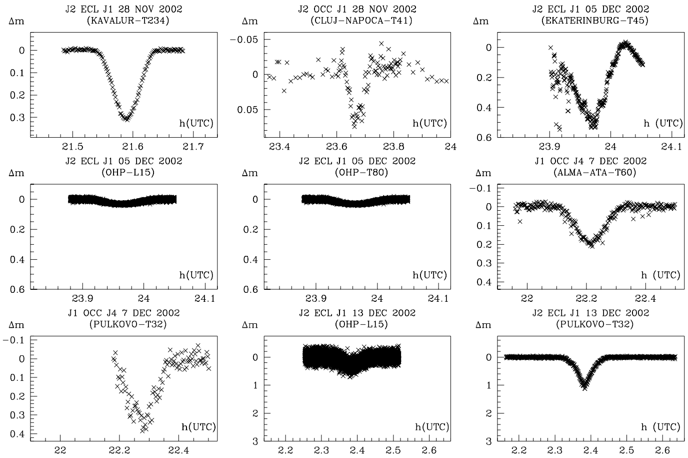


Fig. 1. Light curves for the observations of the mutual events of the Galilean satellites in 2002–2003.



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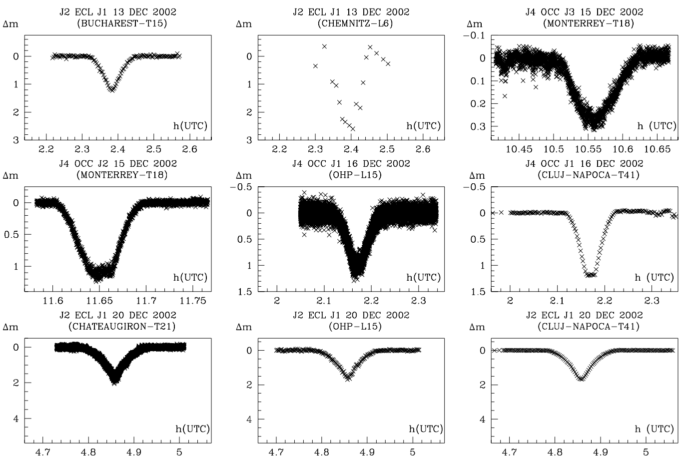
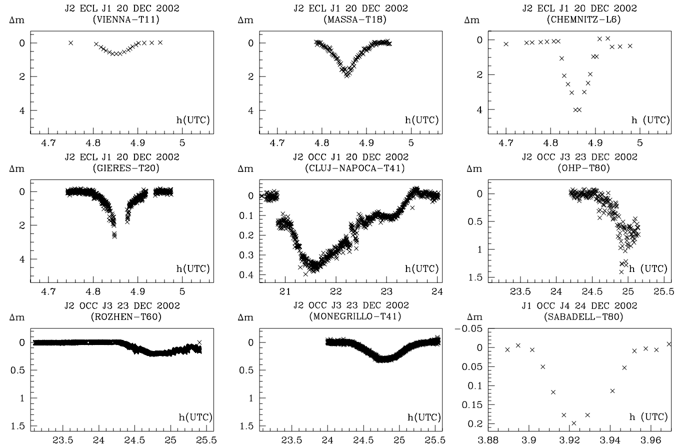


Fig. 3. Light curves for the observations of the mutual events of the Galilean satellites in 2002–2003.



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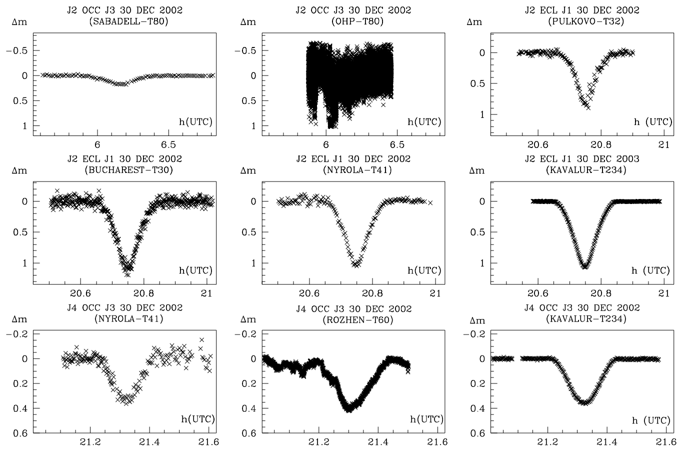

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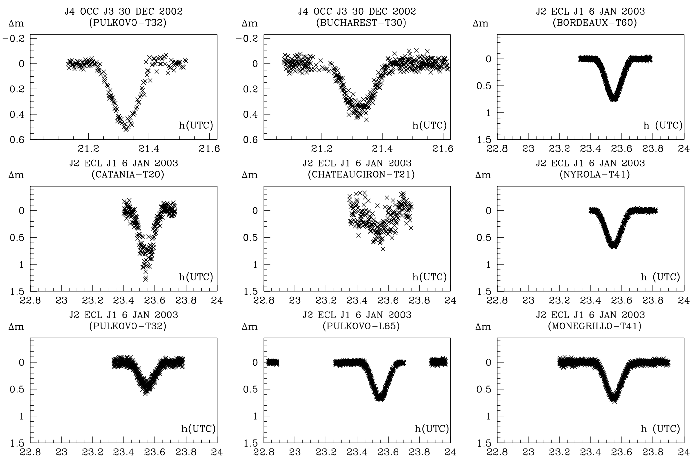

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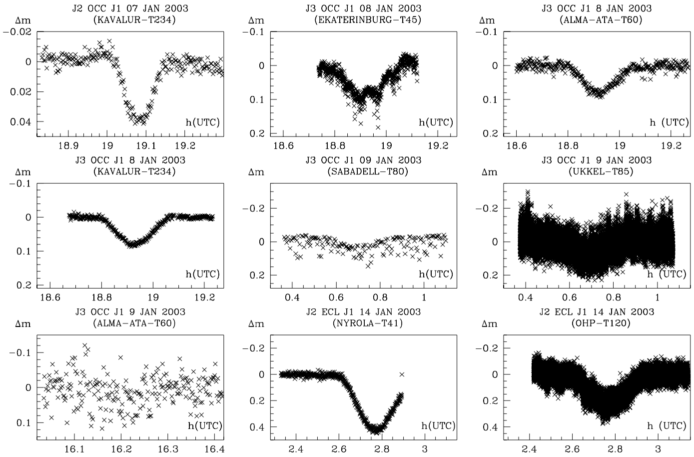

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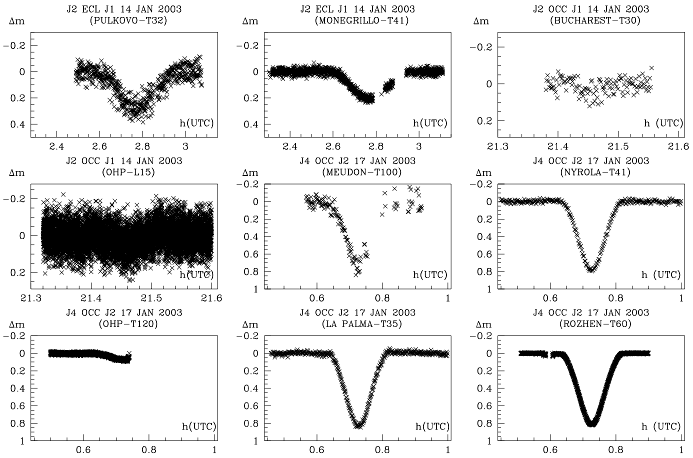

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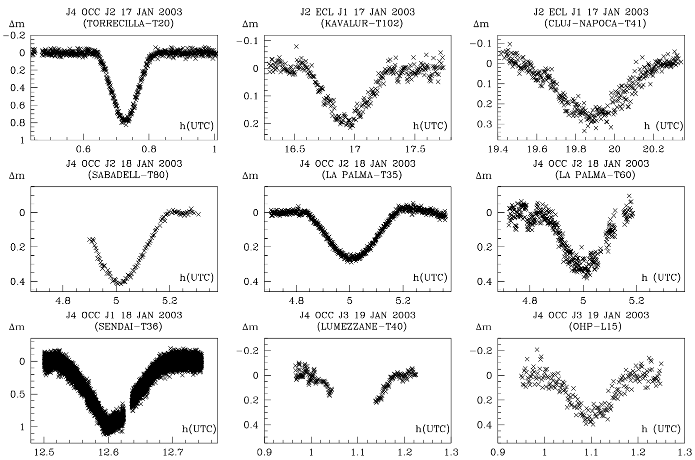

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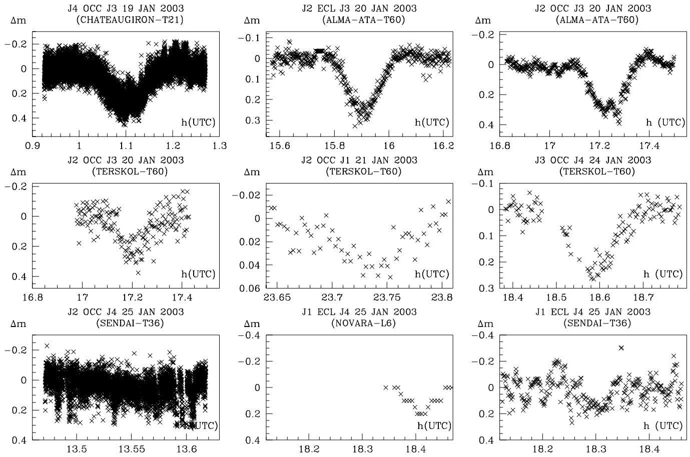

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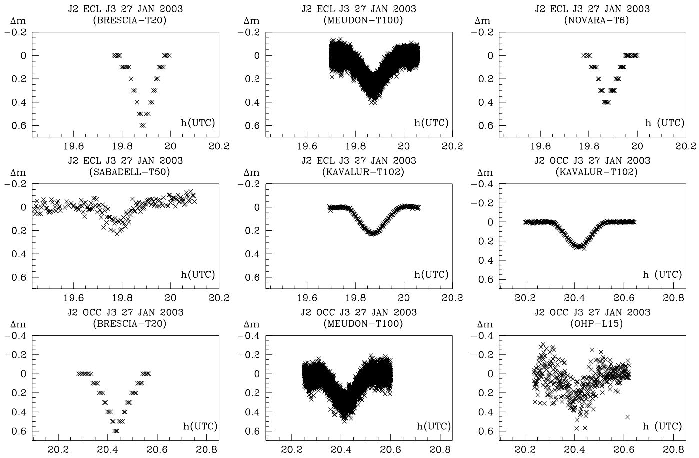

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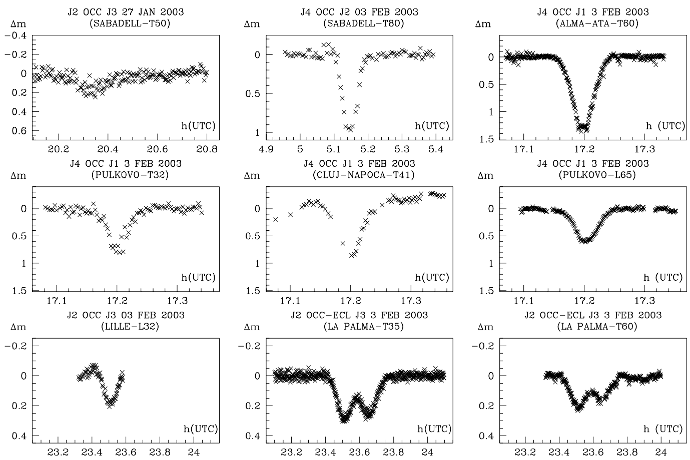

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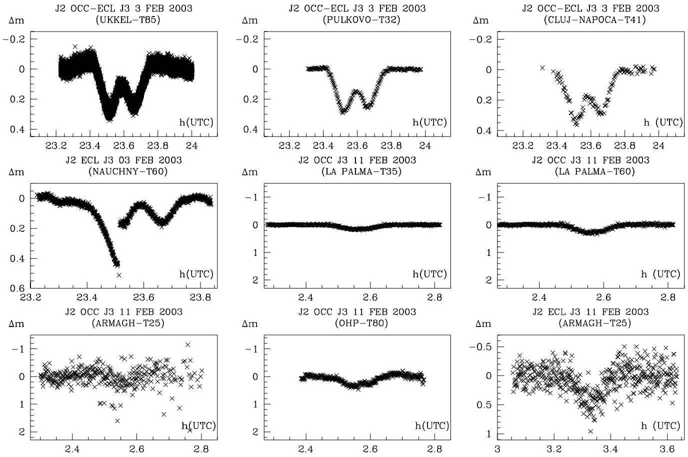

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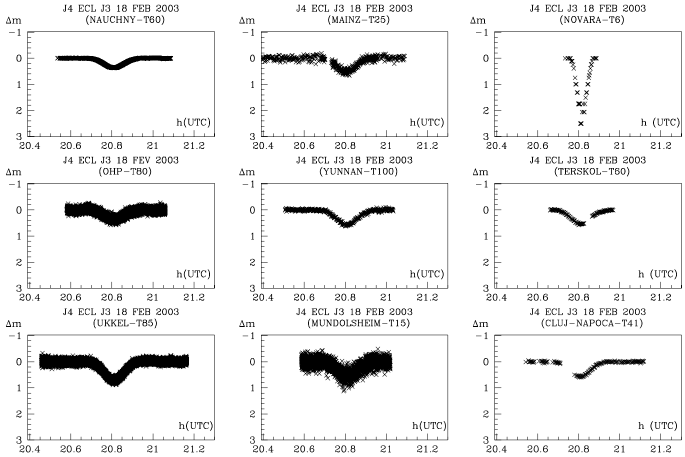

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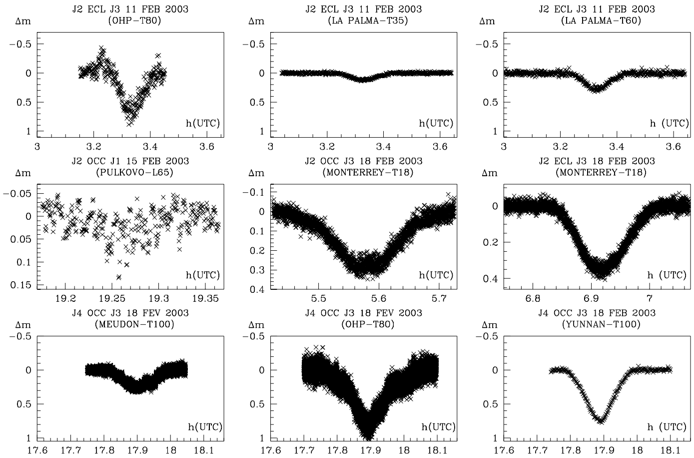

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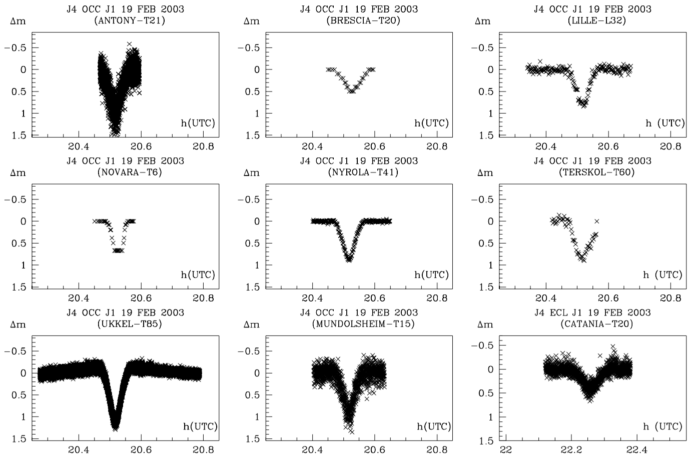

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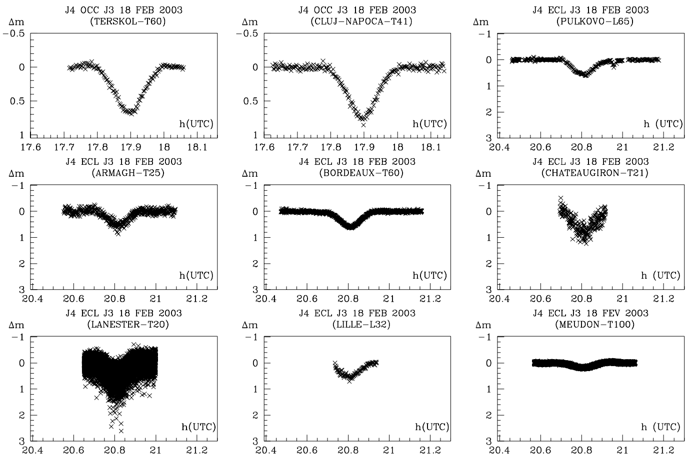

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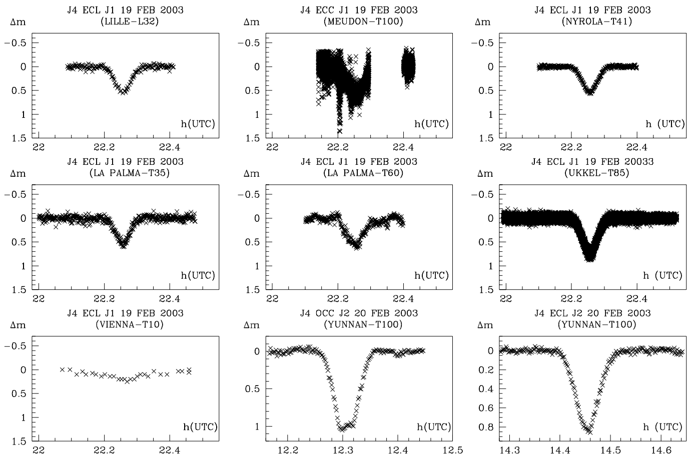

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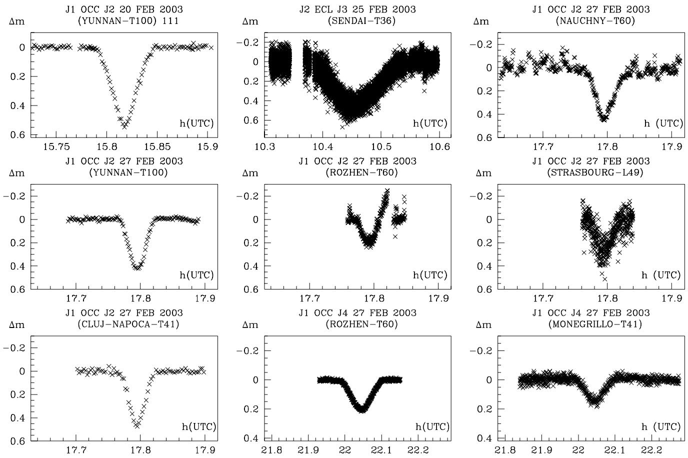

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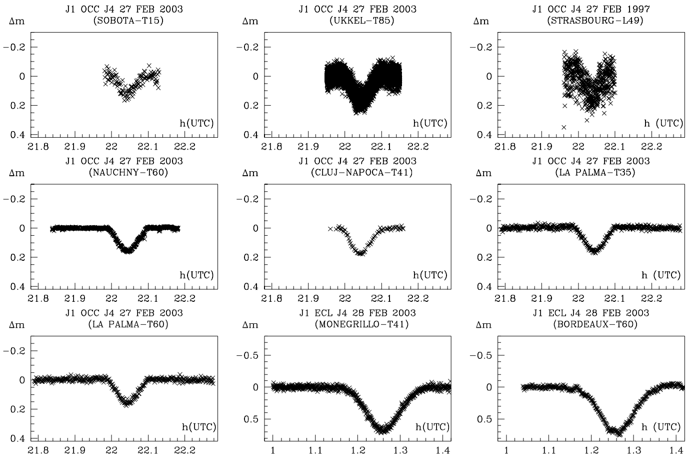

Fig. 20. Light curves for the observations of the mutual events of the Galilean satellites in 2002–2003.

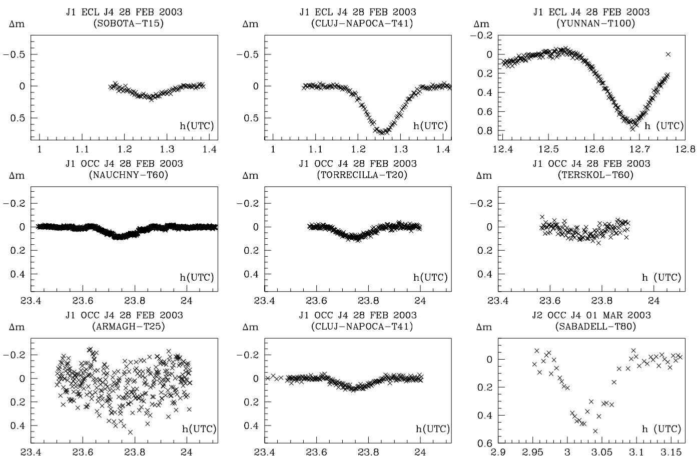

Fig. 21. Light curves for the observations of the mutual events of the Galilean satellites in 2002–2003.

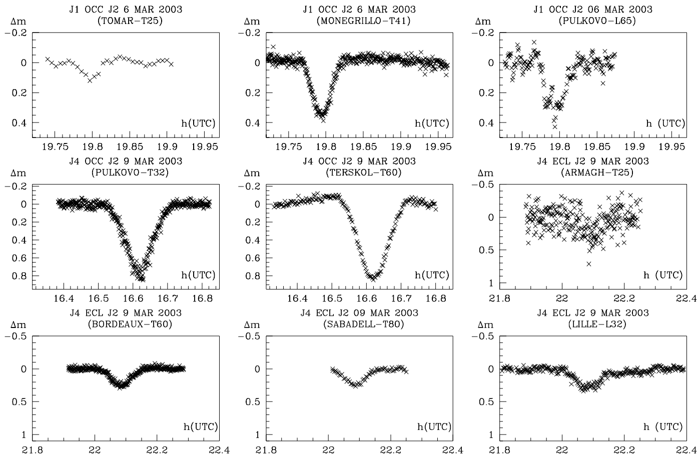

Fig. 22. Light curves for the observations of the mutual events of the Galilean satellites in 2002–2003.

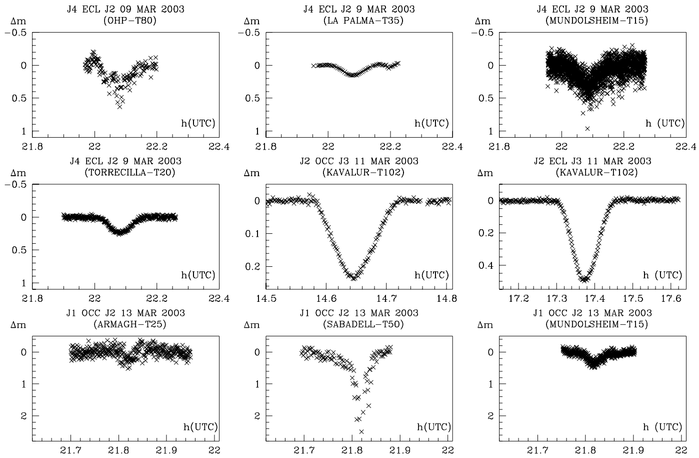

Fig. 23. Light curves for the observations of the mutual events of the Galilean satellites in 2002–2003.

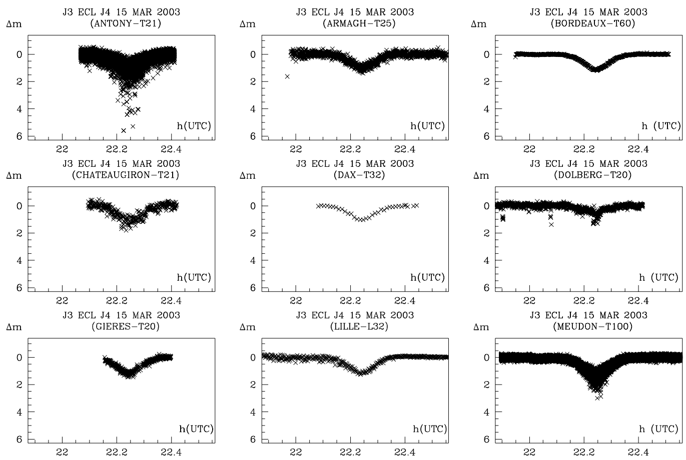

Fig. 24. Light curves for the observations of the mutual events of the Galilean satellites in 2002–2003.

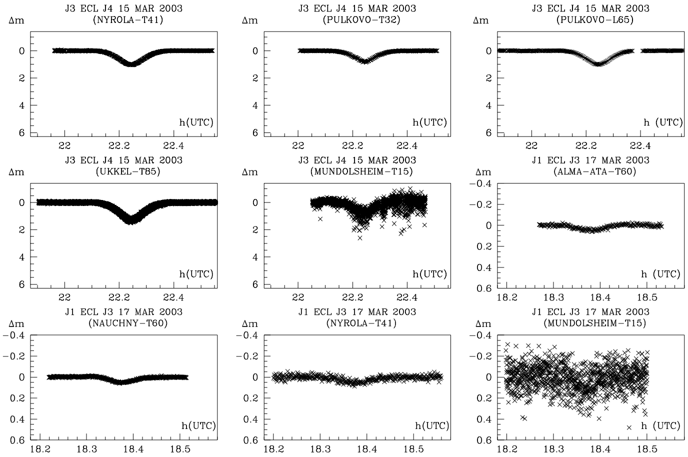

Fig. 25. Light curves for the observations of the mutual events of the Galilean satellites in 2002–2003.

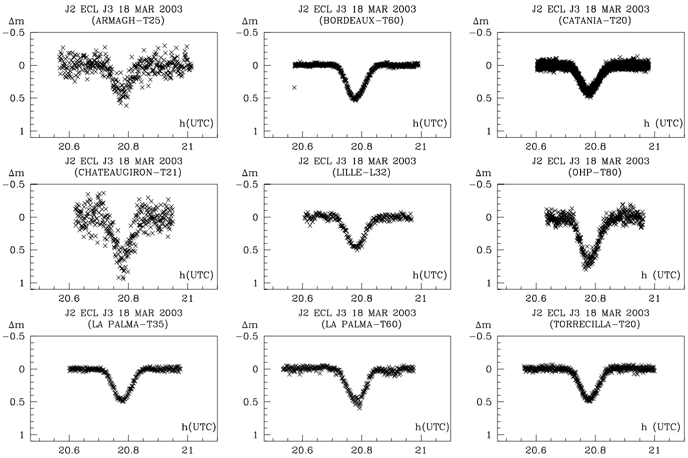

Fig. 26. Light curves for the observations of the mutual events of the Galilean satellites in 2002–2003.

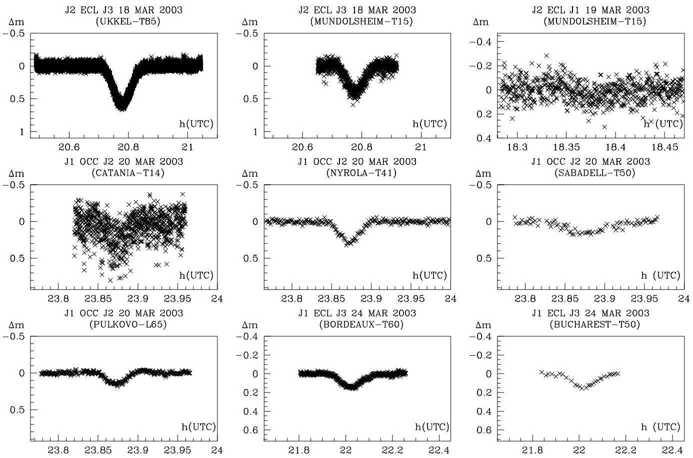

Fig. 27. Light curves for the observations of the mutual events of the Galilean satellites in 2002–2003.

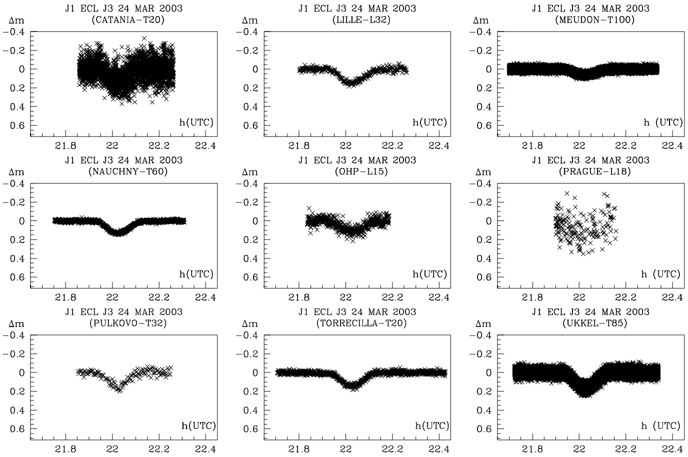

Fig. 28. Light curves for the observations of the mutual events of the Galilean satellites in 2002–2003.

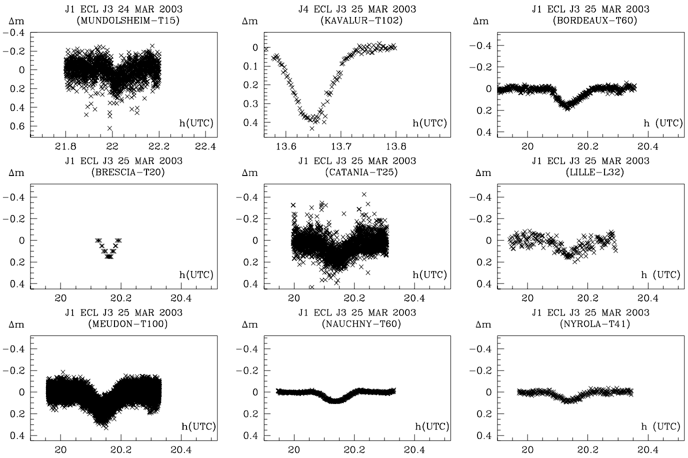

Fig. 29. Light curves for the observations of the mutual events of the Galilean satellites in 2002–2003.

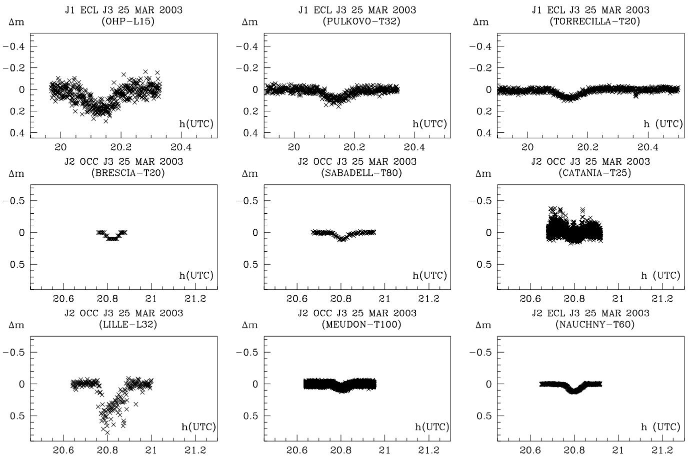

Fig. 30. Light curves for the observations of the mutual events of the Galilean satellites in 2002–2003.

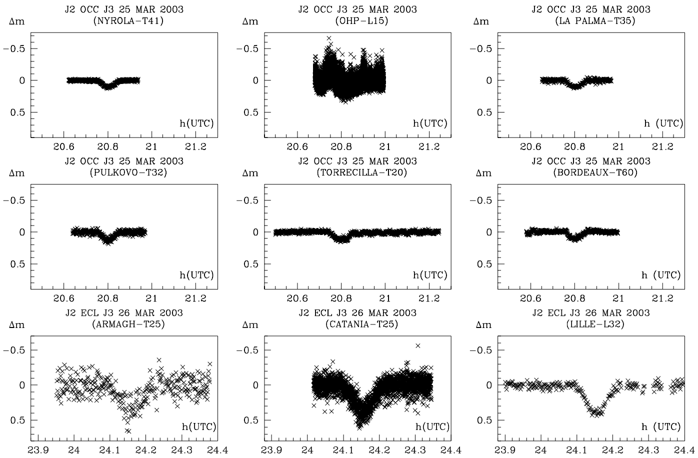

Fig. 31. Light curves for the observations of the mutual events of the Galilean satellites in 2002–2003.

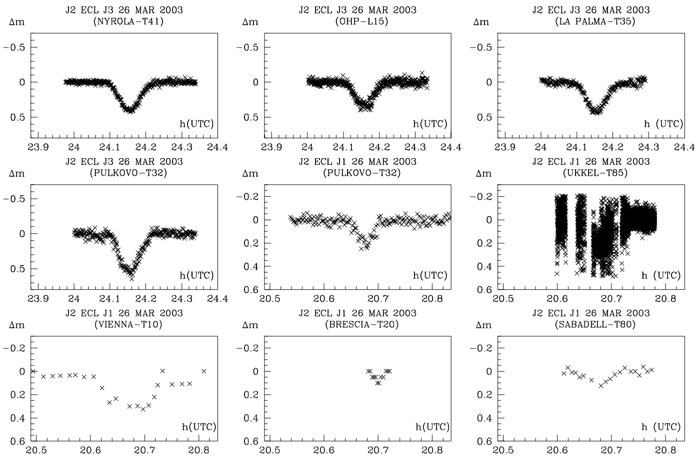

Fig. 32. Light curves for the observations of the mutual events of the Galilean satellites in 2002–2003.

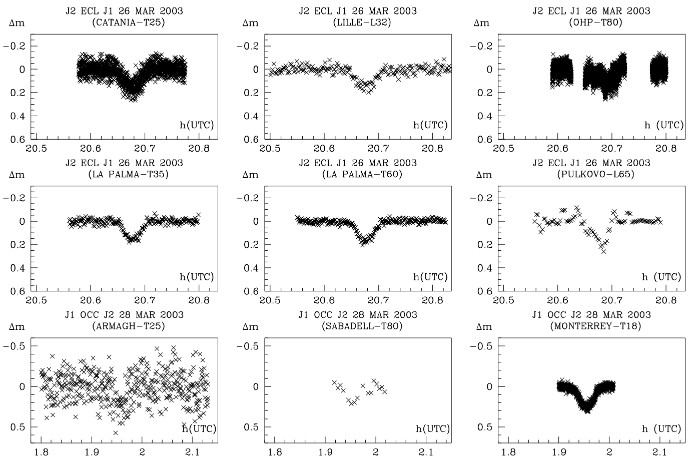

Fig. 33. Light curves for the observations of the mutual events of the Galilean satellites in 2002–2003.

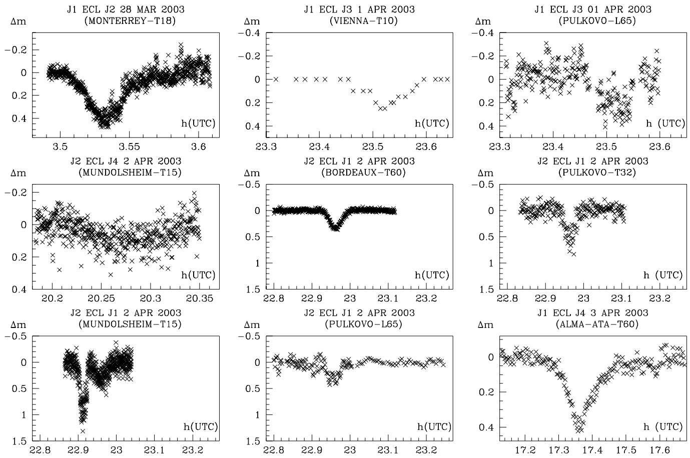

Fig. 34. Light curves for the observations of the mutual events of the Galilean satellites in 2002–2003.

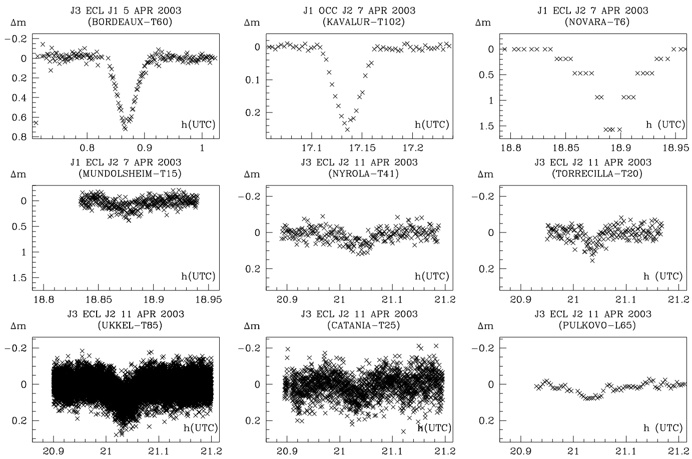

Fig. 35. Light curves for the observations of the mutual events of the Galilean satellites in 2002–2003.

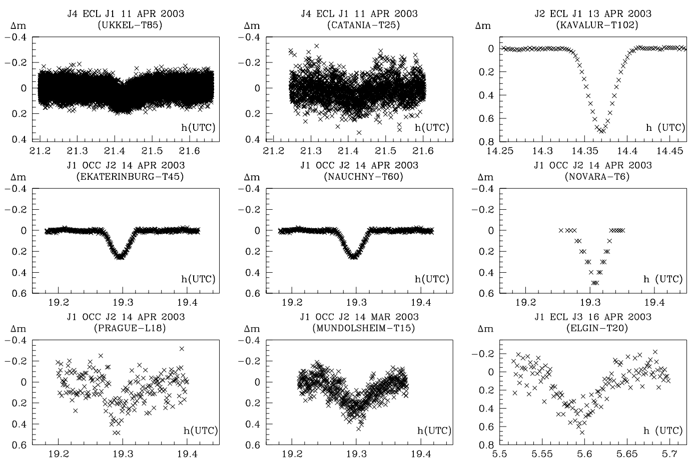

Fig. 36. Light curves for the observations of the mutual events of the Galilean satellites in 2002–2003.

5. The catalogue

5.1. The data

In Table 4, we present the following data for each observed event, where all dates are in UTC:

– predicted time of the event:

1. date (year, month, day) and nature of the event (4O1 means that satellite 4 occults satellite 1; 3E2 means that satellite 3 eclipses satellite 2; P means partial event, A annular, T total, and blank, an eclipse by the penumbra only);
2. beginning of event;
3. maximum of event;
4. end of event;
5. calculated magnitude drop;
6. phase angle in degrees;

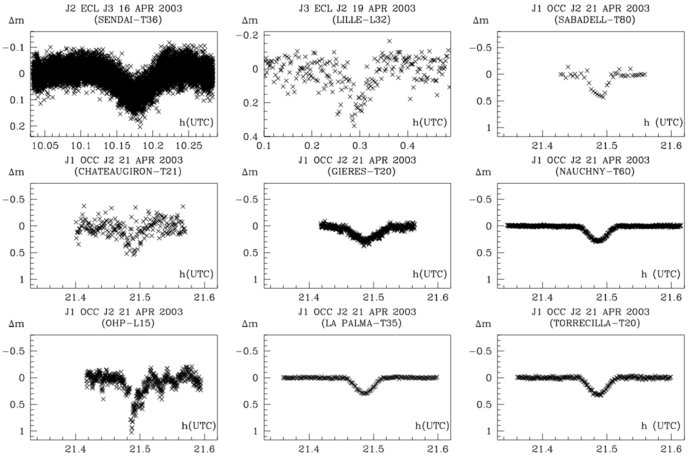

Fig. 37. Light curves for the observations of the mutual events of the Galilean satellites in 2002–2003.

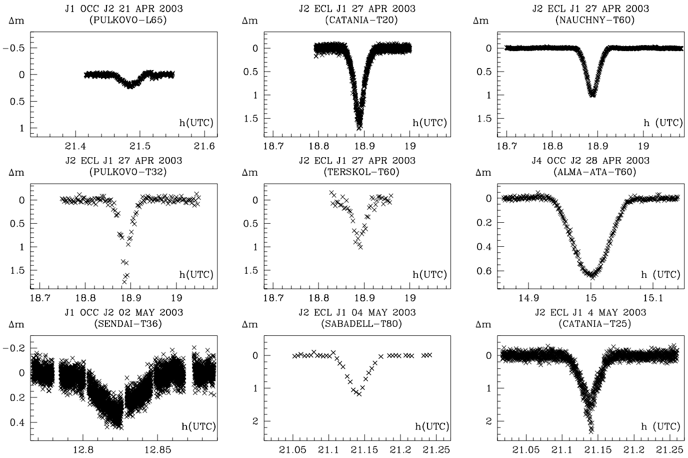

Fig. 38. Light curves for the observations of the mutual events of the Galilean satellites in 2002–2003.

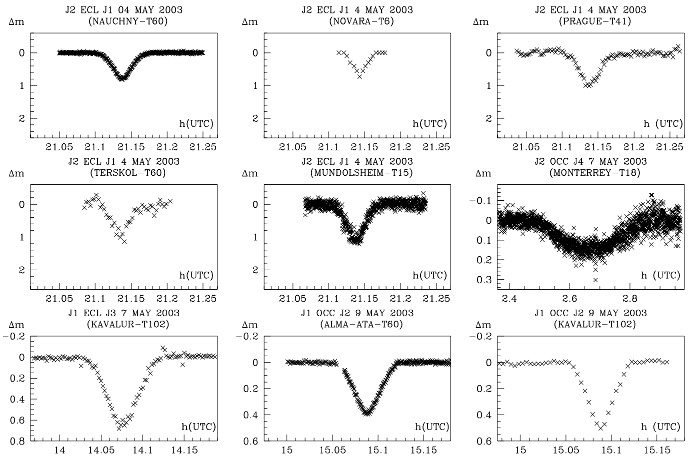

Fig. 39. Light curves for the observations of the mutual events of the Galilean satellites in 2002–2003.

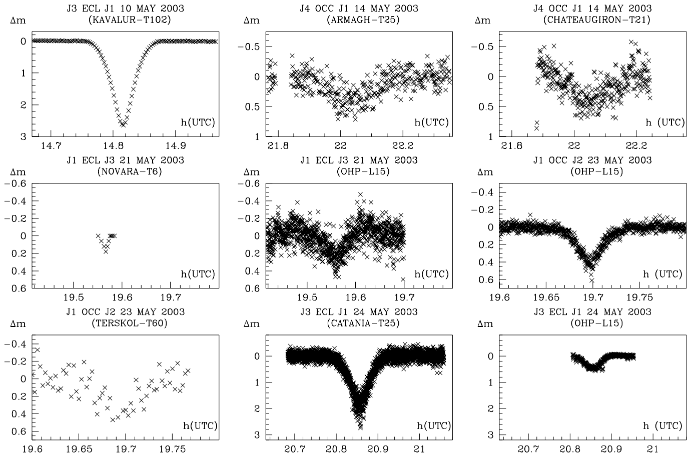

Fig. 40. Light curves for the observations of the mutual events of the Galilean satellites in 2002–2003.

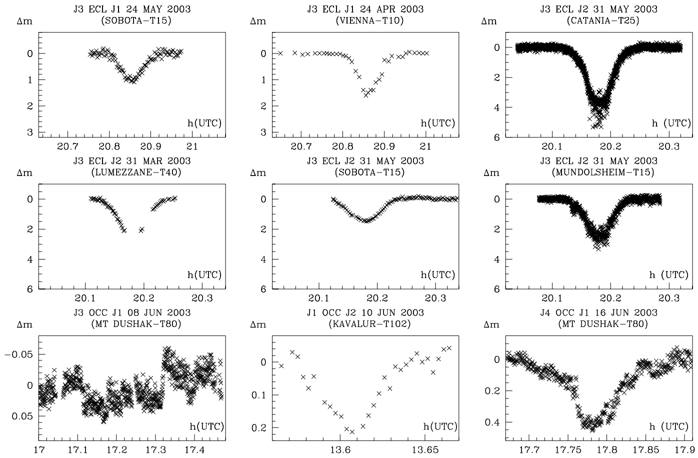

Fig. 41. Light curves for the observations of the mutual events of the Galilean satellites in 2002–2003.

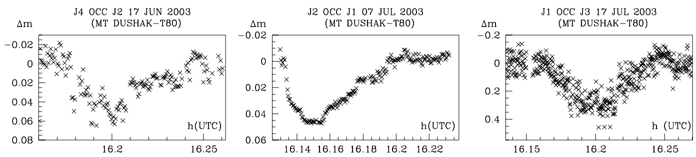

Fig. 42. Light curves for the observations of the mutual events of the Galilean satellites in 2002–2003.

7. apparent distance between satellite and planet in planetary radii.

– for each observation of the above event:
  1. site of observation;
  2. –
  3. observed time of the maximum of magnitude drop and observational error;
  4. –
  5. observed magnitude drop and observational error;
  6. –
  7. –
  8. (C–O) of the observation in seconds of time; these quantities take into account a phase effect by means of the Aksnes et al. (1986) method;
  9. aperture of the telescope in centimeters (T = reflector; L = refractor);
  10. code of the used receptor in column "Recept." (cf. Table 2);
  11. elevation of Jupiter above the horizon in degrees;
  12. elevation of the Sun above the horizon in degrees;
  13. observational conditions in column "Obs. cond.": [0] means no information, [1] means very good conditions, [2] means acceptable, and [3] very difficult conditions;

14. filter used, if any, during the observations in column "Filter"; no filter used is denoted by "-";
15. integration time of the measurements in seconds; a variable integration time is denoted by "v";
16. size of the diaphragm when used;
17. satellites inside the diaphragm, i.e. those taken into account when compiling the light curve (if nothing is indicated, then this is only the eclipsed satellite during the eclipses and both satellites responsible for the occultations).

A corresponding light curve is presented for each observation described in these tables, in which the magnitude drop is indicated in terms of the UTC timescale.

These data and light-curves are available for anyone interested from the electronic database of the Natural Satellite Data Center (NSDC) server on the WEB server[2].

5.2. Discussion

This catalogue intends to provide observational information and reduced data from the PHEMU03 campaign. Another paper (Emelianov 2008) will provide the astrometric data extracted from the light curves.

The quality of each light curve may be assessed either by the errors in the determined parameters (times of both the minimum of light and magnitude drop) or by the appearance of the light curve itself.

As in the previous catalogues of such events, we computed the errors in the determined parameters as follows. The error in the light flux drop was determined from the standard deviation of the fit to the model light curve. The error in the date of the minimum is deduced from the error in the magnitude drop combined with the speed of the decrease in the light flux during the event. This explains why this error depends on the number of points, the integrating time, and the depth of the light curve. Because of this, error bars can only be compared for events observed with the same time constants and, preferably, with the same equipment to be able to derive a reliable an observational error and measurement of the quality of the observation.

6. Conclusion

We have presented the results of the PHEMU03 campaign. This catalogue presents the results obtained by all participants of the campaign who obtained significant results. To be able to observe the maximum possible number of events, it was necessary to organize an international campaign. These phenomena occur every 6 years and can enable accurate astrometric measurements to be completed which are difficult to achieve with other ground-based techniques. Furthermore, they may allow us to determine surface parameters by comparison between light curves and synthetic models. Our experience has demonstrated that past campaigns provided catalogues of data invaluable for astrometric purposes. Accurate astrometric data were deduced from the published observations and used for dynamical purposes. Compared with other types of observations, it is clear that mutual event data have the smallest residuals in the astrometric measurements derived (Lainey et al. 2004).

[2] At the web address http://www.imcce.fr/nsdc or on the ftp server at ftp://ftp.imcce.fr/pub/NSDC/jupiter/raw_data/phenomena/mutual/2003/

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