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The PHEMU15 catalog and astrometric results of the Jupiter's Galilean satellite mutual occultation and eclipse observations made in 2014-2015.⋆,⋆⋆

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ABSTRACT

Aims. During the 2014-2015 mutual events season, the IMCCE, Paris France, and the Sternberg Astronomical Institute, Moscou Russia, lead an international observation campaign to record ground-based photometric observations of Galilean moon mutual occultations and eclipses. We focused on processing the complete photometric observations database to compute new accurate astrometric positions.

Methods. We used our method to derive astrometric positions from the lightcurves of the events. We developed an accurate photometric model of mutual occultations and eclipses, while correcting for the satellite albedos, Hapke's light scattering law, the phase effect and the limb darkening.

Results. We processed 607 lightcurves and we compared the observed positions of the satellites with the theoretical positions from IMCCE NOE-5-2010-GAL satellite ephemerides and INPOP13c planetary ephemeris. The internal precision in equatorial positions is 24 mas, or 75 km at Jupiter. The rms (O-C) in equatorial positions is ±50 mas, or 150 km at Jupiter.

Key words. astronomical databases: miscellaneous – techniques: photometric – planets and satellites: individual: Io – planets and satellites: individual: Europa – planets and satellites: individual: Ganymede – planets and satellites: individual: Callisto – occultations – eclipses – ephemerides

1. Introduction

The Jovian system and the Galilean moons have been studied for their motion, in particular. Their respective dynamical models allow us to constrain their structure and their origin theories.

Photometric observations of mutual events of the Galilean moons are essential to improve their ephemerides, mainly because we are able to extract high-precised astrometric positions of the satellites from the photometry. Moreover, Robert et al. (2017) have recently demonstrated that the positioning accuracy derived form photometric observations still remains more precise than that derived from direct astrometry, even if the use of the most recent Gaia-DR1 catalog (Gaia Collaboration et al. 2016) allowed them to eliminate the systematic errors due to the star references. Thus, our work is crucial for current and future spacecraft navigation (Dirkx et al. 2016), and for dynamical purposes, since the ephemerides are improved by adjusting the new astrometric positions to the theories.

Photometric observations of mutual events of the Galilean moons are essential to improve the ephemerides. Indeed, we can extract astrometric positions of the satellites from the photometry. The determined positioning accuracy is more precise than that derived from direct astrometry (Robert et al. 2017). Then, we can improve the ephemerides by adjusting the astrometric positions to the theories. This work is crucial for current and futur spacecraft navigation, and for dynamical purposes.

In 2014-2015, the Institut de Mécanique Céleste et de Calcul des Éphémérides (IMCCE) and the Sternberg Astronomical

⋆ Full Tables 3 and 4 are available in electronic form at the Natural Satellites DataBase service of IMCCE via http://nsdb.imcce.fr/obsphe/obsphe-en/fjuphemu.html

⋆⋆ Thirty-eight mutual events were recorded at the 1 m telescope of Pic du Midi Observatory (S2P) and at the 80 cm and the 1m20 telescopes of Haute-Provence Observatory.

Table 1. Raw statistics of the PHEMU85, PHEMU91, PHEMU97, PHEMU03, and PHEMU09 campaigns

	1985	1991	1997	2003	2009
Observation sites	28	56	42	42	74
Light curves	166	374	292	377	457
Observable events	248	221	390	360	237
Observed events	64	111	148	118	172

Institute (SAI) organized a worldwide observation campaign to record a maximum of mutual occultations and eclipses of the Galilean moons. In this paper, we present the results of this campaign, with the photometric and astrometric data.

2. The mutual events

Mutual events of the Galilean moons occur when the common plane of their orbits crosses the plane of Jupiter's. This configuration happens every six years when the Jovian declinations of Earth and Sun become zero.

The 2014-2015 period was very favorable since 442 events were observable from 2015-09-01 to 2015-07-20. To compute the predictions of all the 2014-2015 events, we used the IMCCE NOE-5-2010-GAL satellite ephemerides (Lainey et al. 2009) and INPOP13c planetary ephemeris (Fienga et al. 2014). By comparison, only 237 events were observable in 2009 and 360 in 2003. The results of the previous observation campaign can be found in Arlot et al. (2014). In Table 1, we show the raw statistics of the PHEMU85, PHEMU91, PHEMU97, PHEMU03, and PHEMU09 campaigns. We observe a constant increase in the numbers of the observation sites, of the light curves, and of the observed events. This denotes the increase in the interest of the non-professional community in these campaigns.

We have already demonstrated, during the previous campaigns, that photometric records of mutual events are accurate enough for astrometric purpose, and that our method provides a high positioning accuracy (Arlot et al. 2014). More recently, Robert et al. (2017) have demonstrated that the positioning accuracy derived from photometry of mutual events still remains more precise than that derived from direct astrometry.

3. The PHEMU15 campaign

3.1. Report

Following the previous mutual event campaign successes, we organized PHEMU15, an international observation campaign to record as many events as possible. To fill in an eventual lack of data due to poor weather, we encouraged observers in different countries to acquire events, and to observe the same events from various longitudes.

During this campaign, we observed 236 events and a same event was recorded 17 times. We received 641 lightcurves and astrometric results were calculated for 607 of them. 34 lightcurves could not be used for several reasons such as a non event detection, an observation after the minimum, or an observation of an occultation and an eclipse at the same time. Figure 1 shows the raw statistics of the observed events and numbers of corresponding observations.

We distinguished the source of data within two categories. The Source I gathered the photometric observations made by the IMCCE observation team. Records were realized at Pic du Midi Observatory (IAU code 586) and Haute-Provence Observatory (IAU code 511). We extracted the satellite flow for 38 events to produce the lightcurves before treatment. Then, the Source A gathered other observations made by professional or non-professional observers around the world. The satellite flow were directly extracted by the observers who transmitted their lightcurves to the IMCCE for treatment.

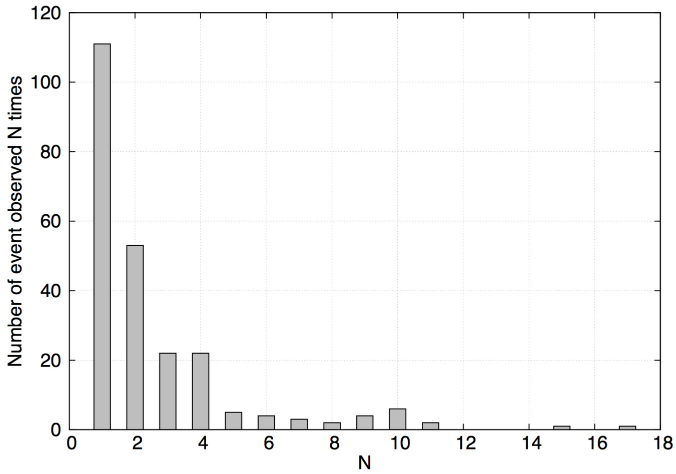

Fig. 1. Raw statistics of the number of events observed N times.

3.2. Observation sites

74 observation sites were involved in the 2014-2015 campaign. For several sites, more than one telescope were used to record events. We have introduced a special code to identify each observation facility. A correspondence between the facility and their conventional code is given in the database[1] with the astrometric results in electronic form at the Natural Satellites DataBase (NSDB) service of IMCCE. Table 2 shows raw statistics of the different observation sites of the campaign. Starting from the lefthand column, we provide the number of observations received O, the number of observations R for which astrometric results were calculated, the number of observations N for which the light curves showed no events, the number of observations S for which an occultation and an eclipse occurred at the same time and for which the astrometric results could not be obtained, the location of the observer, and if relevant their IAU code.

4. Lightcurves reduction

4.1. Photometric reduction

Mutual events can be recorded with a video camera which provides a movie, or a CCD camera which provides fits images. In both cases, we need the most precise datation, that is to say better than 0.1 s. Most of the time, aperture photometry is applied for the light flux extraction. This technique consists of summing the illuminated pixels of a satellite, and subtracting the contribution from the sky background. Many events were recorded with at least two satellites in the camera field, the occulted or eclipsed satellite, and one to three reference satellites. At least, one reference satellite is needed to minimize an eventual flux inconsistency due to the weather.

[1] Full explanation table is available in electronic form at the NSDB service of IMCCE via `http://nsdb.imcce.fr/obspos/phemuAR/explan2_e.htm`

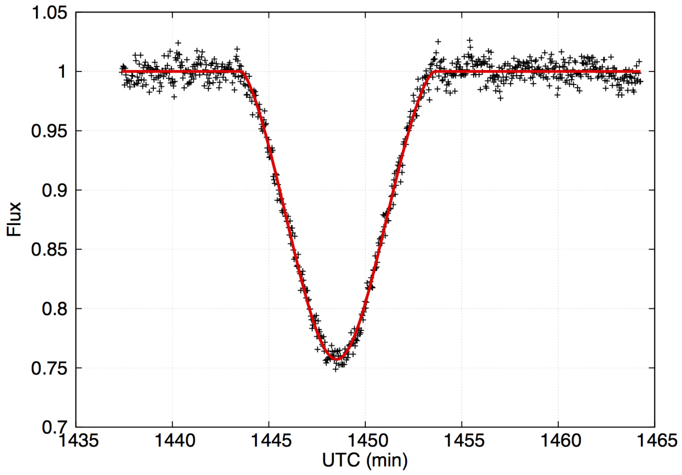

Fig. 2. Europa occults Io on 06 January 2015. Dots denote observational data, line denotes the model adjustment. The lightcurve is perfectly modeled and the observation is not noisy.

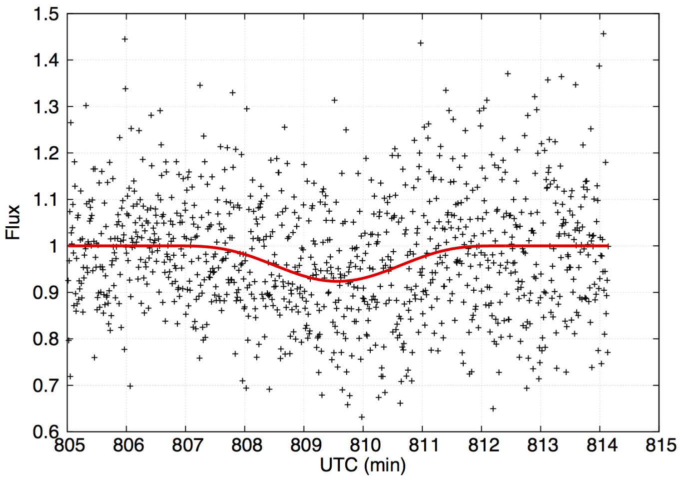

Fig. 3. Io eclipses Ganymede on 21 January 2015. Dots denote observational data, line denotes the model adjustment. This observation shows a grazing event with a small magnitude drop. The signal is noisy and could be improved with a longer integrating time for each point.

For each event, we created a file containing metadata in the head lines, and following lines containing the UTC date, the measured flux (or magnitude) for the satellites involved in the event, and the flux (or magnitude) for the reference satellites. These files are provided in the IMCCE database as well.

Figures 2 to 6 show lightcurve examples and corresponding model adjustments. Figures 4 and 5, in particular, show one event recorded by two different observers. The longer integration for each point in Figure 5 gives a signal less noisy than in Figure 4.

4.2. Astrometric reduction

We used the astrometric reduction method developed in Emelianov (2003), and in Emelyanov & Gilbert (2006) to compute the astrometric results. This method has already been used in Arlot et al. (2014) and in our solution, we used the IMCCE NOE-5-2010-GAL satellite ephemerides. The method consists in fitting the event parameters to the observed light curve.

Astrometric results are given as intersatellite differential (X, Y) coordinates in equatorial positions, where $X = \Delta\alpha \cos\delta$

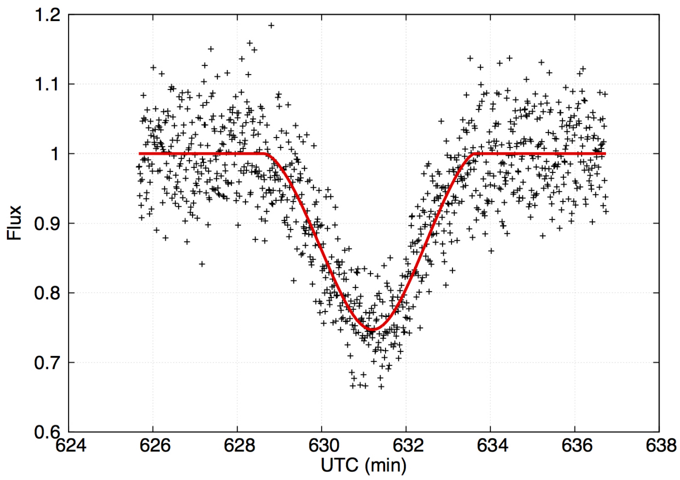

Fig. 4. Europa occults Io on 22 March 2015. Dots denote observational data, line denotes the model adjustment. The observation is noisy.

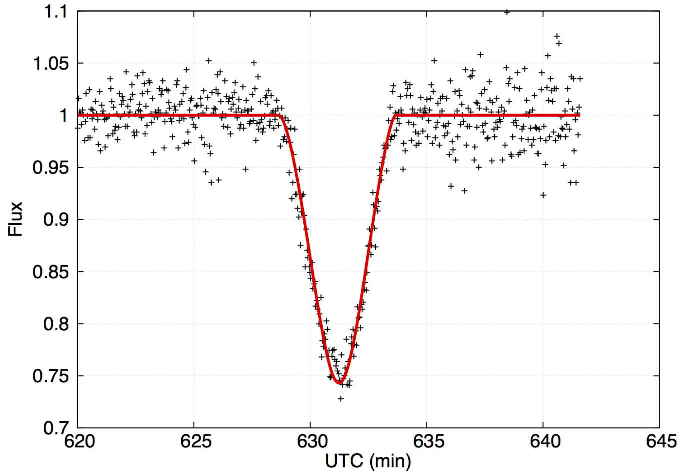

Fig. 5. Europa occults Io on 22 March 2015. Dots denote observational data, line denotes the model adjustment. This is the same event than in Figure 4, but the integration time was different.

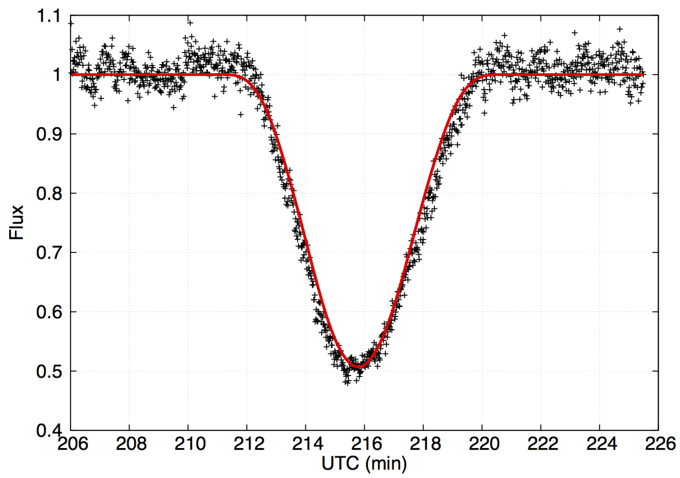

Fig. 6. Io eclipses Ganymede on 27 February 2015. Dots denote observational data, line denotes the model adjustment. This is a full eclipse.

and $Y = \Delta\delta$ at the instant of the satellites closest approach t^*. $\Delta\alpha$ and $\Delta\delta$ are the position differences in right ascension and declination, respectively, given in the 'occulting minus occulted' or 'eclipsing minus eclipsed' directions. We provide astrometric results in an ICRS topocentric frame in the case of mutual occultations, and in an ICRS heliocentric frame in the case of mutual eclipses. Note that in the case of full events, only the position angle P can be determined.

Once we fitted the event parameters to the observations, we were able to determine the normalized photometric measurements and the corresponding modeled light flux. The flux outside the event is 1, and 0 if the satellite is completely occulted or eclipsed.

5. The resulting databases

5.1. Photometric results database

The normalized lightcurves are available in electronic form at the NSDB service of IMCCE. We composed a catalog which consists in 607 files, corresponding to the observations for which astrometric results were calculated. For each line of the files, we provide the UTC observation time in minutes starting from 0h at the event day, and the normalized photometric measurements of the event. By the end, we provide the modeled light flux calculated from the event parameters fitted to the observed lightcurve. Examples of modeling are shown in Figures 2 to 6, as red lines.

5.2. Astrometric results database

The astrometric results are divided in two sections. The first section is related to the events for which the differential (X, Y) coordinates could be computed, the second to the full events for which only the position angle P could be computed. In this last section, the apparent relative position of the satellite measured across the apparent trajectory can not be fixed definitively, and therefore position angles can be determined only up to ± 180 degrees.

Table 3 gives an extract of the astrometric results of the first section. Starting from the lefthand column, we provide the observatory code, the event type, the UTC date, the differential $(X(t^*), Y(t^*))$ coordinates in equatorial positions, the internal errors characterizing the accuracy of the photometry estimated via the least-squares method, the (O-C) computed from the NOE-5-2010-GAL satellite ephemerides characterizing the agreement between theory and observations, the angular separation s, the position angle P, an estimation of the results quality and reliability Q, and the normalized flux minimum level S_{min}. The Observatory code identifies not only the observatory but also the precise site coordinates and the used telescope. Details are given in the explanation text accompanying the astrometric results in NSBD database. In the event type column, N_aoN_p denotes an occultation with the active (occulting) satellite number N_a and the passive (occulted) satellite number Np. N_aeN_p denotes an eclipse with the active (eclipsing) satellite number N_a and the passive (eclipsed) satellite number Np, as well. The position angle and the angular separation are respectively defined as:

$$\tan P = \frac{Y}{X}, \qquad s = \sqrt{(X)^2 + (Y)^2}$$

The estimation of the results quality and reliability Q could be:

- 0 for nominal determination of the position coordinates,
- 1 for the doubtful cases of photometric data (low-quality photometry, or divergent results for a same event, or a large shift in the time moment).

Table 4 gives an extract of the astrometric results of the second section. Starting from the lefthand column, we provide the observatory code, the event type, the UTC date, the position angle P, the internal error, and the (O-C) of the apparent relative satellite position along the satellite track computed from the NOE-5-2010-GAL satellite ephemerides. The internal accuracy corresponds to our positioning accuracy along the relative apparent path including the astrometric errors at 1σ, obtained with the least-squares method.

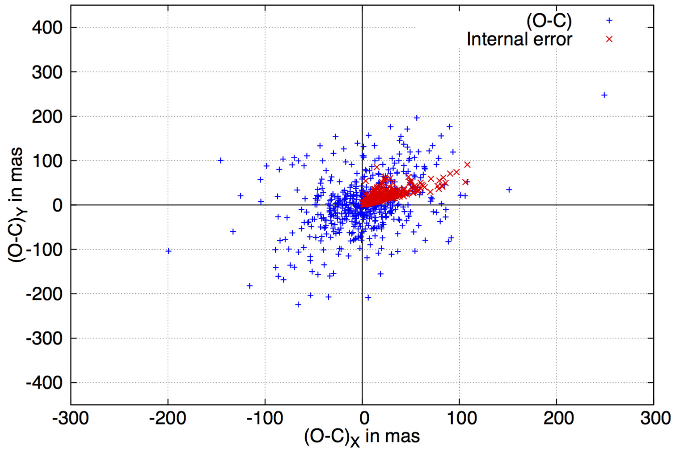

Fig. 7. Equatorial (O-C) according to NOE-5-2010-GAL ephemerides. The x-axis shows the RA (O-C) and y-axis the Dec (O-C). Red crosses denote the internal errors.

6. Accuracy of the astrometric results

We compared the positions of the Galilean satellites with their theoretical computed positions given by the NOE-5-2010-GAL satellite ephemerides. The distributions of the (O-C)s in differential coordinates and the corresponding internal errors are provided in Figure 7 and Table 5. They show the difference (RA, Dec) coordinates for individual satellites, hence the observed positions versus positions calculated from NOE-5-2010-GAL ephemerides.

We used $Q = 0$ as an indicator to define the best observations in our set. This concerns 511 observations. Offsets for the observation set are -1.8 mas and 0.1 mas in right ascension and declination, respectively. They are negligible and we may deduce that any mismodeling of photometric corrections remains.

The key point is that the NOE-5-2010-GAL rms (O-C) for all these observations is 49.9 mas. This average rms (O-C) on both right ascension and declination corresponds to our external observation accuracy.

7. Conclusions

The IMCCE and SAI organized the 2014-2015 PHEMU15 international observation campaign of the mutual events of the Galilean satellites. All the photometric observations of mutual occultations and eclipses were reduced. 607 astrometric results were calculated.

The internal precisions in equatorial positions are 23.2 mas and 20.2 mas in right ascension and declination, respectively.

Table 3. Extract of the astrometric results for which the differential coordinates in equatorial positions could be computed.

Obs. code	Type	Date Y M D	UTC h m s	$X(t^*)$ arcsec	$Y(t^*)$ arcsec	σ_X arcsec	σ_Y arcsec	$O-C_X$ arcsec	$O-C_Y$ arcsec	s arcsec	P deg	Q	S_{min}
ADS	4e3	2014 09 11	20 57 26.40	-0.2945	-0.1747	0.0120	0.0358	-0.0239	0.0022	0.3424	239.325	0	0.3619
KIS	3e4	2014 10 07	00 08 47.00	0.0523	0.1717	0.0025	0.0039	-0.0108	0.0913	0.1795	16.950	0	0.1113
KIS	2o3	2014 10 21	02 03 26.25	-0.2812	-0.7463	0.0274	0.0122	0.1930	0.1211	0.7976	200.642	1	0.9532
			...										
ADS	1o2	2014 11 19	18 14 32.65	-0.1432	-0.3692	0.0431	0.0363	0.3751	-0.0387	0.3960	201.197	1	0.7462
KUR	3o1	2014 11 22	16 34 56.93	-0.0954	-0.2483	0.0089	0.0164	-0.1058	-0.2080	0.2660	201.019	1	0.6050
ADS	1o3	2014 11 26	18 37 19.13	0.0962	0.2484	0.0188	0.0204	0.0427	0.0757	0.2664	21.168	0	0.7013
KIS	3o1	2014 12 06	22 15 7.88	0.1542	0.4006	0.0050	0.0049	0.0172	0.1056	0.4292	21.047	0	0.6603
ALM	2e3	2014 12 09	22 43 4.58	-0.2622	-0.7572	0.0137	0.0079	0.0289	0.0707	0.8013	199.098	0	0.9395
ARO	2o1	2014 12 12	23 43 8.80	-0.1194	-0.4123	0.0071	0.0088	-0.0022	-0.0071	0.4292	196.145	0	0.6104
			...										
PIC	2e1	2015 01 06	22 33 28.04	-0.2167	-0.6007	0.0030	0.0016	0.0086	-0.0136	0.6386	199.839	0	0.8647
OHP	2e1	2015 01 06	22 33 27.10	-0.2221	-0.6153	0.0046	0.0024	0.0014	-0.0275	0.6542	199.846	0	0.8778
OHP	2o1	2015 01 07	00 08 38.21	0.1540	0.3869	0.0016	0.0015	-0.0012	-0.0167	0.4164	21.705	0	0.7584
OHP	2o1	2015 01 07	00 08 20.36	0.1611	0.4046	0.0099	0.0094	-0.0463	0.0218	0.4355	21.705	0	0.7690
PIC	2o1	2015 01 07	00 08 38.78	0.1532	0.3847	0.0017	0.0015	-0.0005	-0.0195	0.4141	21.707	0	0.7572
PIC	2o1	2015 01 07	00 08 38.53	0.1524	0.3828	0.0051	0.0046	-0.0020	-0.0211	0.4120	21.704	0	0.7561
			...										
MUR	1e2	2015 06 13	08 51 46.45	0.2086	0.5111	0.0069	0.0047	-0.0115	-0.0088	0.5520	22.200	0	0.7138
KUR	1e2	2015 06 13	08 51 44.75	0.2104	0.5153	0.0070	0.0046	-0.0175	-0.0015	0.5566	22.208	0	0.7199
FLY	1e2	2015 06 13	08 51 57.88	0.1724	0.4226	0.0119	0.0088	0.0049	-0.1188	0.4564	22.191	0	0.8138
CAC	1e2	2015 06 16	22 01 31.55	0.2055	0.5024	0.0126	0.0088	-0.0162	-0.0260	0.5428	22.246	0	0.7014
UMA	2o1	2015 06 26	04 53 47.33	0.0969	0.2535	0.0083	0.0073	-0.0211	-0.0199	0.2714	20.918	0	0.7423

Notes. The full table is available at the NSDB service of IMCCE.

Table 4. Extract of the astrometric results for which only the position angle could be computed.

Obs. code	Type	Date Y M D	UTC h m s	P deg	σ arcsec	$O-C$ arcsec
VBO	2o4	2014 11 27	22 08 52.26	200.934	0.0044	0.0164
ALM	3o1	2014 11 29	19 23 51.85	21.076	0.0111	0.0510
ADS	3o1	2014 12 14	18 49 25.02	20.128	0.0027	0.0059
ALM	3o1	2014 12 14	21 31 13.25	22.385	0.0015	0.0336
		...				
ELG	2e1	2015 02 22	02 45 15.28	200.622	0.0091	0.0223
ADS	2o1	2015 02 25	15 10 05.34	19.706	0.0035	0.0268
SEN	2o1	2015 02 25	15 10 10.26	19.640	0.0040	0.0538
VBO	2o1	2015 02 25	15 10 04.58	199.669	0.0018	0.0207
KOU	2e1	2015 02 25	15 55 10.32	20.606	0.0032	0.0194

Notes. The full table is available at the NSDB service of IMCCE.

Table 5. Details of the astrometric positions in mas, according to NOE-5-2010-GAL ephemerides.

	$X(t^*)$	$Y(t^*)$
$\overline{(O-C)}$	-1.8	0.1
rms (O-C)	39.2	60.7
Internal errors	23.6	24.6

The rms (O-C)s in equatorial positions are ± 39.2 mas and ± 60.7 mas in right ascension and declination, respectively. These results are better than those of the previous PHEMU09 campaign, and confirm the high interest in observing mutual events.

The next campaign will begin in January, 2021 and end in November, 2021. The occurence will be less favorable since the maximum of events will occur at the conjonction of Jupiter with the Sun. The 2021 campaign will be more favorable to the southern hemisphere, due to Jupiter declination.

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Table 2. Observation sites for the PHEMU15 campaign. We provide the number of observations received O, the number of observations R for which astrometric results were calculated, the number of observations N for which the light curves showed no events, the number of observations S for which an occultation and an eclipse occurred at the same time and for which the astrometric results could not be obtained, the location of the observer, and if relevant their IAU code.

O	R	N	S	Site, Country	IAU code
Source I					
11	10	1	0	Haute-Provence Obs., France	511
27	24	3	0	Pic du Midi Obs., France	586
Source A					
48	47	1	0	Desert Springs, Australia	
3	3	0	0	Umatilla, USA	
41	41	0	0	Scottsdale, USA	
10	10	0	0	Kuriwa Obs., Australia	E28
9	7	0	2	Tunis, Tunisia	
16	15	0	1	La Couyere Astro. Center, France	J23
36	35	1	0	Murrumbateman, Austrialia	E07
14	14	0	0	Puig d'Agulles, Spain	
8	8	0	0	Tangra Obs., France	E24
5	5	0	0	Elgin, USA	440
5	5	0	0	Toulon, France	
10	10	0	0	Kourovskaya, Russia	168
8	8	0	0	Chaneyville, USA	
16	12	4	0	Mundolsheim, France	
5	5	0	0	Cogolin, France	
18	17	0	1	West Park Obs., England	Z92
5	5	0	0	Itajuba, Brazil	874
5	5	0	0	Iguacu, Brazil	X57
2	2	0	0	Como, Italy	C13
1	1	0	0	Arnold, USA	
3	3	0	0	Vesqueville, Belgique	231
11	11	0	0	Newark, USA	H95
2	1	1	0	Baronnies Provencales Obs., France	B10
7	7	0	0	Waikanae, New Zealand	
1	1	0	0	Kingman, USA	
5	4	1	0	Marseille, France	
6	6	0	0	Tielt, Belgium	
2	2	0	0	Dax Obs., France	958
2	2	0	0	Hyères, France	
3	3	0	0	Siena, Italy	K54
6	4	1	1	Trebur, Germany	239
1	1	0	0	Gardnerville, USA	
9	9	0	0	Montigny-le-Bretonneux, France	
2	2	0	0	Malemort-du-Comtat, France	
2	1	1	0	Darfield, New Zealand	
2	2	0	0	Gretz-Armainvilliers, France	A07
4	4	0	0	Cabudare, Venezuela	
2	2	0	0	Nikolaev, Ukraine	089
1	1	0	0	La Grimaudière, France	
6	3	3	0	Flynn, Australia	
7	7	0	0	Egeskov Obs., Danemark	
4	3	1	0	Salvia Obs., France	I73
11	11	0	0	Biesenthal, Germany	
2	2	0	0	Maidenhead, England	I64
6	6	0	0	Oberkrämer, Germany	
1	1	0	0	Wokuhl-Dabelow, Germany	
6	6	0	0	Rokycany Obs., Czech Republic	K61
6	6	0	0	Berlin, Germany	
1	1	0	0	Slovice, Czech Republic	
1	1	0	0	Fouras, France	
24	24	0	0	Vainu Bappu Obs., India	220
13	12	1	0	Horice, Czech Republic	
14	13	1	0	Alma-Ata, Kazakhstan	210

Table 2. continued.

O	R	N	S	Site, Country	IAU code
1	1	0	0	Antibes, France	139
12	11	1	0	Sendai, Japan	391
13	13	0	0	Nonndorf, Austria	C47
6	6	0	0	GiaGa Obs., Italy	203
1	1	0	0	Saulges, France	I73
1	1	0	0	Wanaka, New Zealand	
2	0	0	2	Dienville, France	
2	2	0	0	Gassin, France	
1	1	0	0	Le Mesnil-Saint-Denis, France	
44	44	0	0	Pulkovo Obs., Russia	084
2	2	0	0	Naperville, USA	W08
7	7	0	0	Pulkovo-Kislovodsk, Russia	C20
4	4	0	0	Voronezh, Russia	
17	16	1	0	Bucharest, Romania	073
6	6	0	0	Laval, Canada	818
28	23	3	2	Armagh Obs., Northern Ireland	981
4	4	0	0	Athens, Greece	066
2	2	0	0	Nyrola Obs., Finland	174
12	12	0	0	Praha, Czech Republic	
641	607	34	9	TOTAL	