Natural satellites mutual phenomena observations: achievements and future

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Abstract

Astrometry of Solar system objects needs to perform observations regularly since the motions are fast and the dynamical models need sample of data on long intervals of time.

The goal of this paper is to show that some phenomena occurring during the equinox on the giant planets are worth to be observed. Past experience has shown the interest of such observations which should be continued in the future due to their relevant contribution to improve the dynamical models.

Using the best ephemerides of the natural planetary satellites, we calculate the next phenomena to occur in order to prepare the future observational campaigns.

We provide in this paper the tables of the dates of the next phenomena as their observational conditions which depends on the opposition and the declination of the planet.

Past observations provided particularly accurate data, better than all the other ground based observations and we encourage observations in the next future especially for planetary systems for which no space mission is planned.

Key words: astrometry, natural planetary satellites, celestial mechanics

1. Introduction

The progress in dynamical modeling of natural planetary satellites needs to provide accurate astrometric observations made on a long interval of time in order to be able to quantify the parameters of the motion and the secular effects due to tidal dissipation (Lainey et al. 2009). We would like to emphasize the observation of the mutual phenomena of the natural planetary satellites which has been performed since the 1970s and which should continue in the future. The interest in such observations is that they are not correlated to the current direct astrometric observations made through imaging and calibrated thanks to reference star catalogues. The reduction of the mutual phenomena observations depends only on the physical knowledge of the satellites: size in kilometers and albedo of the surfaces. Mutual phenomena observations are photometric observations: their astrometric accuracy depends only on the timing of the phenomena and the measurement of the magnitude drop which will be both transformed in astrometric positions on the celestial sphere.

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2. Description of the phenomena

The eclipses of the Galilean satellites by the shadow of Jupiter are known and observed for centuries. They were used for the building of the first ephemerides and the fit to the first dynamical models. Unfortunately, these observations are not accurate enough to be used nowadays. The disappearance of the satellites in the shadow of Jupiter is not well-defined: the refraction of the light in the upper atmosphere of Jupiter makes the timing of the eclipses uncertain. For this reason, eclipse observations were replaced since the end of the XIXth century by photographic observations and by CCD observations at the end of the XXth century.

During the 1970s, using the first computers, it was possible to predict rare phenomena, the mutual eclipses and occultations between the satellites. A mutual eclipse occurs when a satellite enters the shadow of another satellite and disappears for an observer; a mutual occultation occurs when a satellite passes on the disk of another satellite as seen from a ground-based observer. Since the satellites have no atmosphere, the photometric signal observed during the phenomenon is very sharp and more easy to model. The prediction of such phenomena was very sensitive to the inclination of the satellite orbits on the equatorial plane of Jupiter so that the calculations were complex. Note that the natural planetary satellites have their orbits near the equatorial plane of their planet so that, when the Sun crosses this plane (when its planetocentric declination is close to zero), the satellites will eclipse each other for several minutes during about 6 months (satellites are not points but are small disks). This occurrence takes place at the time of equinox on the planet (every 6 years for Jupiter, every 14 years for Saturn and every 42 years for Uranus). Similarly, when the Earth crosses the equatorial plane of a planet, mutual occultations will occur. Since the Earth and the Sun are close together as seen from the planetary satellites, the mutual eclipses and occultations occur simultaneously. We show in figures 2, 6 and 8 the planetocentric declinations of the Sun and the Earth for the future mutual phenomenon seasons. More details are provided on these phenomena in Arlot and Stavinschi (2007).

3. Past observations

Before the 1970s, mutual phenomena of the Galilean satellites of Jupiter have been observed by chance when observing the regular eclipses by the planet. The predictions were uncertain, many predicted phenomena did not occur. In fact, the diameter of the satellites is less than one arcsec so that an error of one arcsec in the ephemerides had two results: first, shift the phenomenon in time if the error is mainly in longitude but make the phenomenon nonexistent if the error is in latitude. Predictions became better when the ephemerides achieved better than 0.5 arcsec accuracy and when computers were available to make long calculations including the whole dynamical model.

Besides the Galilean satellites, it appeared that satellites of Saturn and Uranus presented mutual phenomena since they were also orbiting in the equatorial plane of their planet. The satellites of Saturn present mutual phenomena every 14 years. They are fainter than the Galilean satellites but the main problem is the bright ring making more difficult the photometric measurements of the mutual phenomena. The satellites of Uranus present mutual phenomena every 42 years. Due to the distance, they are faint and appear close to the planet. They are difficult to observe but if so, the spatial accuracy is the same as that for the Galilean satellites since the measurement is made relatively to the size of the satellites in kilometers which is well known since the observation by the Voyager space probe.

3.1. *Previous observational campaigns*

Mutual phenomena have been observed since the season of 1973 starting with the Galilean satellites. In 1979-80, mutual phenomena of the Saturnian satellites occured and observations were made. For each successive occurrence to follow, observational campaigns were organized for both systems. In 2007 mutual phenomena of the Uranian satellites occured and observations were made: however, the next occurrence will be in 2049. As a consequence, the observations from the 2007 campaign will remain unique for few decades. Table 1 provides a list of all the observations made and published catalogues of data, the number of observing sites, observations and the reference to predictions and results. All the data are available on the Natural Satellites data Base (NSDB) at the address: http://nsdb.imcce.fr/obspos/obsindhe.htm at "Phenomena".

3.1.1. *The Galilean satellites*

The Galilean satellites are easy to observe : they are bright and mutual phenomena may be observed through a small instrument. Table 2 provides the list of all the observations made, the number of observing sites and the number of phenomena observed. Note that the number of observations has grown with time because of the increasing availability of the CCD cameras to amateurs. The number of observations depends on several parameters and a worldwide collaboration is necessary to observe as much as phenomena since phenomena occur anytime. Tthe Northern hemisphere observers have more favorable conditions when the declination of Jupiter is positive (negative for the Southern). Note that for the season of 1979, the proximity between the Jovian conjunction and the Jovian equinox, associated to bad meteorological conditions made the observations difficult.

Year after year, the observers became more numerous even though they were less in the Southern hemisphere. In 2009 and 2015, it was suggested to observe the eclipses of the inner satellites by the Galileans. Such observations are difficult: the inner satellites are very faint and close to the bright disk of Jupiter. Eclipses of Amalthea were observed in 2009 and 2015 and an eclipse of Thebe was observed in 2015 (cf. table 2). Specific features were used for such observations either a mask on Jupiter or the use of infrared filters needing then a larger telescope.

For each campaign, the published observational results were different:

- in 1973, 1979, 1985 and 1991 only dates of the minimum and magnitude drops were provided (Aksnes et al. 1984, Arlot et al. 1974, Arlot et al. 1982, Dourneau 1982, Arlot et al. 1992, Arlot et al. 1997).

- in 1997 and 2003, dates of the minimum and magnitude drops were provided (Arlot et al. 2006a, Arlot et al. 2009) and also the astrometric relative positions X, Y in Vasundhara et al. (2003), Emelyanov & Vashkovyak (2009) and Emelyanov (2009).

- in 2009 and 2015, astrometric relative positions X, Y were provided (Arlot et al. 2014, Saquet et al. 2018). In (Dias-Oliveira et al., 2013) impact parameters and the central instants (instant of time associated with the impact parameter) were deduced from 25 mutual eclipses and occultations between the Galilean satellites observed from Brazil in 2009. Their method of photometric reduction is

Table 1
Characteristics of the previous observational campaigns (No is the number of observations made during the occurrence and Ns is the number of observing sites) ; Jupiter° means eclipses of inner satellites by the Galileans; * means that the results are under the form of minimum of light and ** means that the results are under the form of relative right ascension and declination

Mutual phenomena	No	Ns	Processing method by:	References to results	Predictions
Jupiter 1973	46	18	Aksnes	Aksnes et al. 1984*, Arlot et al. 1974*	Arlot 1973, Brinkmann & Millis 1973
Jupiter 1979	19	11	Aksnes	Aksnes et al. 1984*, Arlot et al. 1982*	Arlot 1978
Saturn 1980	14	6	Aksnes	Aksnes et al. 1984*, Dourneau 1982*	Aksnes & Franklin 1978
Jupiter 1985	166	28	Arlot	Arlot et al. 1992*	Arlot 1984
Jupiter 1991	374	56	Arlot	Arlot et al. 1997*	Arlot 1990
Saturn 1995	66	16	Noyelles	Noyelles et al. 2003**	Arlot & Thuillot 1993
			Arlot	Thuillot et al. 2001*	
Jupiter 1997	292	42	Vasundhara	Vasundhara et al. 2003**, Arlot et al. 2006a*	Arlot 1996
			Emelyanov, Vashkovyak	Emelyanov & Vashkovyak 2009**	
Jupiter 2003	377	42	Emelyanov	Emelyanov 2009**, Arlot et al. 2009*	Arlot 2002
Uranus 2007	41	19	Emelyanov	Arlot et al. 2013**, Christou et al. 2009**	Arlot et al. 2006b
Jupiter 2009	457	74	Emelyanov, Varflolomeev	Arlot et al. 2014**	Arlot 2008
Jupiter° 2009	2	3	Christou	Christou et al. 2010*	
Saturn 2009	33	17	Emelyanov	Arlot et al. 2012**	Arlot & Thuillot 2008
Jupiter 2015	609	75	Emelyanov	Saquet et al. 2018**	Arlot et al. 2014
Jupiter° 2015	4	2	Saquet	Saquet et al. 2016**	

Table 2
Mutual phenomena of the Galilean satelltes: dates, occurrences, number of observing sites and number of observations. 2009° and 2015° correspond to eclipses of the inner satellites Amalthea and Thebe by the Galileans

Years	1973	1979	1985	1991	1997	2003	2009	2009°	2015	2015°
sites of observations	27	11	28	56	42	42	74	2	75	2
declination of Jupiter in deg. at equinox	-19	+18	-19	+19	-17	+19	-13	-13	+16	+16
distance equinox-opposition in days	112	162	57	108	3	52	53	53	2	2
number of observations made	94	22	166	374	292	377	457	3	609	4
number of observed phenomena	65	8	64	111	148	116	172	3	236	3

explained in their paper.

Note that for the astrometric relative positions X, Y the results may differ from an author to another since depending on the reduction model continuously improved. The light-curves were provided only starting from the 1985 campaign, allowing to re-do the reduction.

3.1.2. *The Saturnian satellites*

After the interesting observations of the mutual phenomena of the Galilean satellites in 1973, new observations were made in 1979-1980 either for the Galileans and for the Saturnian satellites, the equinox on Saturn occurring in March 1980, near the opposition of the planet and the Sun. Observations appeared to be very difficult because of the bright ring too close to the satellites. Table 2 provides the circumstances of the occurrences of observation.

As for the Galileans, the published observational results differ from one campaign to another:

- in 1980, only dates of minimum and magnitude drops (Aksnes et al. 1984, Dourneau 1982)

Table 3
Mutual phenomena of the Saturnian satellites: dates, occurrences, number of observing sites and number of observations.

Years	1980	1995	2009
sites of observations	6	16	19
declination of Saturn in deg. at equinox	+4	-5	+6
distance equinox-opposition in days	11	65	156
number of observations made	14	66	26
number of observed phenomena	13	43	20

- in 1995, dates and magnitude drops in Thuillot et al. (2001) and astrometric relative positions X, Y in Noyelles et al. (2003).
- in 2009, only astrometric relative positions X, Y were provided in Arlot et al. (2012).

The light-curves were provided only for 1995 and 2009.

Table 4
Mutual phenomena of the Uranian satelltes: dates, occurrences, number of observing sites and number of observations.

Years	2007
sites of observations	19
declination of Uranus in deg.at equinox	-7
distance equinox-opposition in days	88
number of observations made	41
number of observed phenomena	27

3.1.3. *The Uranian satellites*

The mutual phenomena of the Uranian satellites are very rare (every 42 years) and occured in 2007. Due to the scarcity of these phenomena and because of the too few astrometric data available on this system, a special effort has been made to observe these phenomena. Due to the large distance of Uranus to earth, the satellites are faint (magnitude 14 to 16) and close to the planet (10 to 50 arcsec at elongation). Observations in infrared wavelengths were made on large telescopes (apertures from 2 to 10 meters): the planet was very darkened and the satellites became easier to observe. Some observations were made in the optical with small telescopes (apertures from 20 to 50 centimeters) but only the phenomena occurring far from the planet were observed. Table 4 provides the information on the campaign of 2007.

For the Uranian satellites, astrometric relative positions X, Y were provided in Arlot et al. (2013), Assafin et al. (2009) and in Christou et al. (2009). The light-curves were provided. Note that most of the observations were made in the Southern hemisphere suitable to observe negative declination.

3.2. *The observers and the observational equipment*

It is interesting to see the progress in the equipment of the observers years after years and to deduce the best equipment to be used in the future. At the beginning of the observations, only professional astronomers (Pro) were able to observe and record the phenomena. Amateurs (Am) were able to record the phenomena (the magnitude of the Galilean satellites is from 4 to 5 allowing observations with a very small telescope).

3.2.1. *Pro*

In fact, an observer of a mutual phenomenon has very few choices for a detector. During the first campaigns, only photoelectric photometers were available. The protocol of observation was very demanding but the photometric accuracy was very good. At the beginning, the access to UTC was not so straight forward. A radio receiver was necessary and the synchronisation of the recorder was made to the nearest tenth of a second of time, not better. Knowing that the satellites are moving at about 10 kilometers per second, an error in timing of 0.1 second of time corresponded to one kilometer. The time scale was the main cause of error leading to rejected observations.

In the 1980s, CCD detectors appeared replacing the photoelectric photometer. The observations were more easy to make but the photometric calibration was harder to make and the accuracy of the observations decreased using these new devices. The main problem is to understand the characteristics of the device used to record the observation. Some characteristics of cameras widely sold for different uses (not only astronomy) are not provided to the users making the photometric calibration difficult.

3.2.2. *Am*

During the first occurrences, amateurs were only spectators of the mutual phenomena, not being able to record them. However, the visual observers of variable stars tried to make visual photometric observations of the mutual phenomena. They used the Argelander method: they estimate the magnitude of a star referred to a nearby fixed star in degrees. A Galilean satellite not involved in the phenomenon was chosen as fixed star. However, the speed of the phenomena (a change of several magnitudes during a few minutes of time) made the photometric calibration uncertain and the light curve poorly sampled.

As soon as the amateurs were equipped with reliable recording devices, we invited them to make observations: we needed to enlarge our observational network worldwide since an phenomenon is observable only from 30% of the surface of the Earth.

The last campaign was associated to a French project of participative astronomy allowing the amateurs to join easily the campaign. Publications were made in amateur journals (Arlot, 2014c) and conferences given in amateur congresses (Arlot, 2018). Table 5 shows the distribution of the observing site for the 2015 campaign. The success of the project is obvious as seen by the number of French sites which provided useful data.

3.2.3. *The evolution of the observers*

The first observers were professional astronomers using 50 cm-telescope or larger. They were photometrists using a photoelectric photometer. Some amateurs tried to make visual observations using the methods developed for variable star observation.

Table 6 provides the evolution of the use of telescopes and receptors for the observation of the mutual phenomena. Seven Jovian occurrences allowed the observation of the mutual phenomena of the Galilean satellites and about 1800 observations were made. At the beginning, large telescopes managed by professional astronomers equipped with single channel photoelectric photometers were the more common systems of observations. From 1985, 2D receptors such as CCD cameras appeared and were used allowing recording a reference object at the same time as the occulted or eclipsed satellites: observations were possible even in difficult conditions such as twilight or fog. The prob-

Table 5
Number of observatories and observers in each country participating in the 2015 campaign of observations of mutual occultations and eclipses of the Galilean moons.

Country	Number of observatories	Number of observers
Australia	5	5
Belgium	2	2
Brazil	2	1
Canada	1	1
Czech	4	4
Denmark	1	1
England	2	2
Finland	1	1
France	22	36
Germany	6	5
Greece	1	2
India	1	3
Italy	3	9
Japan	1	1
Kazakhstan	1	4
New Zealand	3	3
Northern Ireland	1	3
Romania	1	4
Russia	4	15
Spain	1	1
Tunisia	1	1
Ukraine	1	2
USA	9	6
Venezuela	1	1
24	75	113

lem was to record images acquired with high temporal frequency (more than one image per second) that was difficult at the beginning of the use of the CCDs. The progress of that type of 2D receptors led to the disappearance of the 1D receptor for the 2009 occurrence. At the same time, the contribution from amateurs observations grew rapidly due to increase of the sensitivity of the receptors allowing using small telescopes. Specific training of the observers was made in order to learn the basis of photometry and also to understand the need of the use of an accurate time scale linked to UTC. Thanks to the not expansive CCD or CMOS cameras, the part of the amateur participation in the observations became essential, allowing to get a large number of observations. Increasing the number of observations will allow to solve photometric problems due to lack of data.

Table 6
Evolution of the size of the telescopes and of the receptors: the number of telescopes used for the observations may be larger than the number of observing sites.

Occurrences	Size of $< 60cm$ amateurs	telescopes $\geq 60cm$ professionals	Photometry 1D	2D
Jupiter				
1973	4	20	24	0
1979	3	7	10	0
1985	12	12	21	3
1991	37	19	39	17
1997	35	10	15	30
2003	34	15	8	41
2009	52	10	0	62
2015	79	16	0	95
Saturn				
1980	0	6	6	0
1995	5	11	8	8
2009	11	8	0	19
Uranus				
2007	4	11	0	15

3.3. *Results and precision*

The reduction of the first observations was very simple: the disks of the satellites were supposed to be uniform and the photometric light curve was supposed to be symetrical. Moreover, the time of minimum of light flux was supposed to be the time of minimum of distance. Observers did not try to go further in their reduction because they were satisfied of their results: the accuracy of their data was better than the one of previous observations either photographic plates or eclipses by Jupiter. However, the light curve might have a good photometric accuracy allowing a better reduction. Note than for the first campaigns, the diameters of the satellites were unknown so that we had to deduce them from the observations of the first mutual phenomena. After receiving the measurements of the radii of the satellites by the Voyager space probes, the reduction used these values making the results more reliable.

From the observational campaign of 2003, a better model for the reduction was introduced (Emelyanov, 2003) in order to take into account the not-uniform disk of the satellites. From the light curve, astrometric relative positions between the satellites were calculated: indeed, the reduction of the light flux depends on the relative coordinates of the moons and one may solve the reverse problem i.e. retrieve astrometric data from the light curves measured during the mutual occultations or eclipses. However, the reduction in astrometric data from the photometry of satellites during their mutual phenomena is a very complex and difficult process mainly because of the complex description of light scaterring and because of the lack of photometric data on the satellites.

The method used to derive astrometric data from photometry of mutual occultations and eclipses of planetary satellites had been first proposed in the 1970s by Aksnes and Franklin (1976), Aksnes et al. (1984) and developed further by Vasundhara (1994) and Noyelles et al. (2003). The model of phenomena was somewhat approximate in these works. Another method for processing photometric observational data and retrieving astrometric results was developed by Emelyanov (2003) and Emelyanov and Gilbert (2006).

The following effects are taken into account:
- various laws of light scattering by a rough surface;
- variation of reflective properties over the satellite surface.
- wavelength-dependent solar limb darkening.

We used the Hapke scattering laws considered in planetology (Hapke 1981, 1984). Hapke analyzed what is so far the most detailed and general law of scattering by the surface of a celestial body. We could only find two complete sets of published Hapke parameters for the Galilean satellites. The first paper (McEwen et al. 1988) gives the Hapke parameters for the rough surface of the satellite Io. The authors of the second paper (Domingue & Verbiscer 1997) refined the Hapke function for rough surfaces. The scattering function includes a set of empirical relations. Similar models for the major moons of Saturn and Uranus were presented by Arlot et al. (2012, 2013).

Light fluxes from each point of the satellite are integrated in the photoreceiver. Each point on the surface has its own scattering properties, and the direction of incidence of solar light and the direction of propagation of reflected light toward the observer differ from one point to another. Any law of light scattering by a point on the satellite surface may be used at this step. A number of parameters governing the reflective properties of the surface of a specific satellite should be determined. One of these parameters is the albedo that is distributed over the satellite surface and is sensitive to surface features.

Note also that the light sensitivity of any photoreceiver varies with wavelength. Therefore, one should take into account the dependence of light scattering on wavelength as well as the properties of the telescope's optical system.

Table 7 provides estimates of the accuracy of the astrometric results obtained from the best observations during the campaigns. Random inaccuracies are the internal accuracies caused by random errors in the photometry. O-C agreements show the root-mean-square values of the differencies between the astrometric results obtained with the ephemerides and those deduced from the photometric observations performed.

Table 7
Estimated astrometric accuracies for the recent observational campaigns. Each value is given separately for the right ascension (RA) and the delination (Decl.). Notation N_b is the number of the best observations taken into account.

Campaign	N_b	Random inaccuracies		O-C agreement	
of observations		RA	Decl.	RA	Decl.
		arcsec	arcsec	arcsec	arcsec
Jupiter, 2003	221	0.026	0.026	0.071	0.094
Jupiter, 2009	365	0.018	0.016	0.046	0.081
Jupiter, 2015	511	0.024	0.025	0.039	0.061
Uranus, 2007	34	0.006	0.004	0.010	0.018
Saturn, 2009	23	0.004	0.004	0.016	0.021

3.4. *40 years of observations of mutual phenomena*

Mutual phenomena are observed since 1973 and 12 campaigns were organized, 8 of them being observations of the phenomena of the Galilean satellites. Did these observations permit to improve the knowledge of the dynamics of the satellites than using only the classical observations, direct imaging or eclipses by Jupiter? The first campaigns allowed to improve the ephemerides as did the other observations but after several campaigns, it appeared that these accurate observations made on a long interval of time was able to quantify small cumulative effects such as an acceleration in the motion of the satellites due to the dissipation of tides. In Lainey et al. (2009), where an acceleration of Io corresponding to the dissipation inside the satellite is detected for the first time, the authors stated that "The observations of mutual phenomena, known to be among the most accurate observations, have a 1σ accuracy of about 0.025 arcsec and provide the best constraint of the satellite orbits for the past decades". Figure 1 shows the compared astrometric accuracy of the mutual phenomena and the classical observations (Arlot et al. 2012a). Mutual phenomena appeared to have a similar accuracy to observations made with the HST. Note that the arrival of the Gaia reference star catalogue will improve the astrometric accuracy of direct imaging of the natural planetary satellites. The accuracy will be closer to the one of the mutual phenomena observations but it is necessary to continue both types of observation to eliminate systematic errors due to observational techniques. Direct astrometric imaging and photometric observations of phenomena are technically very different.

3.5. *Re-reducing the old observations*

In spite of the fact that the results on the dynamics of the satellites are constructive when using the past mutual phenomena observations, one could think about making a new reduction of the old data. The first observations were used only as timings and magnitude drops, not as astrometric relative positions. Moreover, the first photometric

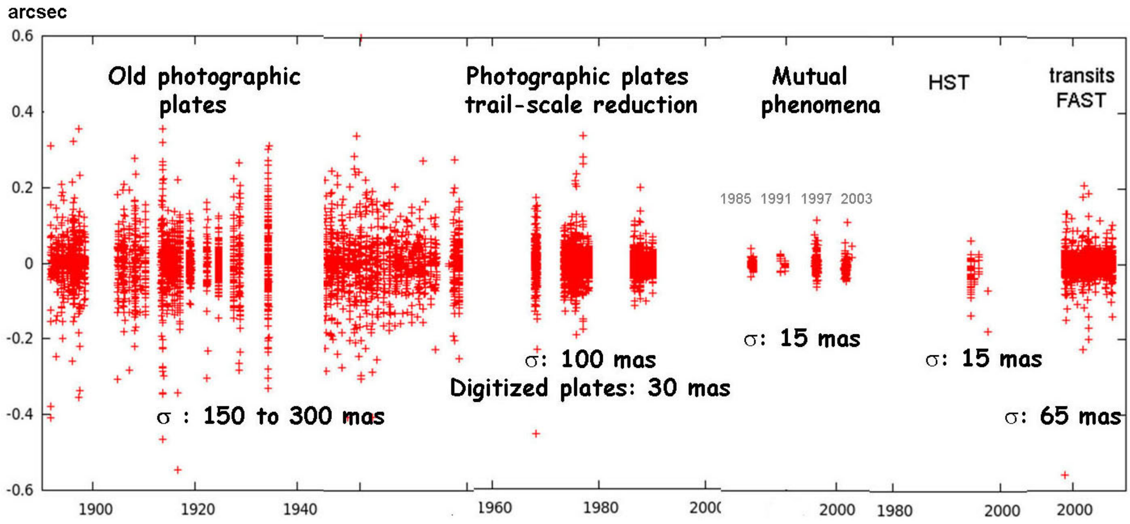

Fig. 1. Residuals for different kinds of observations: mutual phenomena appear to be among the most precise observations.

models were simpler than the new ones. All the data before the campaign of 2003 are worth to be re-analyzed: the precision was good (observation and reduction were made properly) but the accuracy may be improved (the photometric model was too simple) and the photometry made at that time with old photoelectric photometer have a particularly good photometric accuracy which was degraded when using the first CCD detectors.

4. The future phenomena

After demonstrating the value of observing the mutual phenomena of the natural planetary satellites, we would like to present the future occurrences for the organization of future campaigns. Using the best ephemerides of the satellites, we present the predictions of the phenomena and the conditions of observability of each occurrence.

4.1. *Jupiter 2021*

For the satellites of Jupiter (Galilean and inner satellites), the next occurrence corresponds to the next equinox on Jupiter occurring on May 2, 2021 since the opposition will take place on August 20, 2021. 110 days separates both dates and the observations will be easier during this interval of time. The total number of phenomena is 242 occurring from January 3, 2021 to November 16, 2021. Due to the conjunction Sun-Jupiter, only 192 phenomena are observable from March 3, 2021 to November 16, 2021. The number of phenomena per week is shown by figure 2. The declination of Jupiter will be negative (-16 to -12 degrees) around the time of the equinox making the observations easier in the Southern Hemisphere. Figure 4 provides statistics on the distribution of the phenomena during this occurrence.

The inner satellites will be eclipsed by the Galileans: 379 phenomena will be observable from March 3 to September

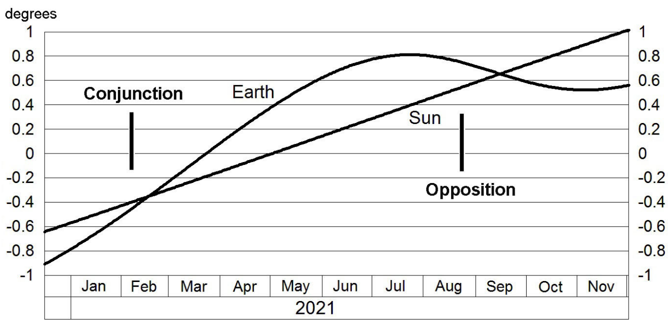

Fig. 2. Parameters of the Earth-Sun-Jupiter configuration during the mutual phenomena of the Galilean satellites in 2021: planetocentric planetoequatorial latitudes (deg) of the Earth and the Sun.

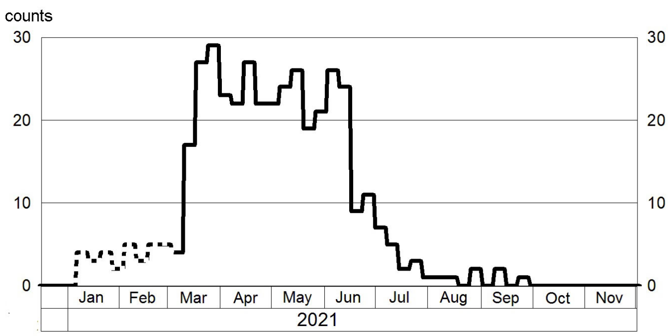

Fig. 3. Parameters of the Earth-Sun-Jupiter configuration during the eclipses of the Inner Jovian satellites in 2021: number of phenomena per week (Monday to Sunday), the dashed sectors correspond to unobservable phenomena.

28, 2021. Figure 3 provides statistics on the distribution of the phenomena during this season.

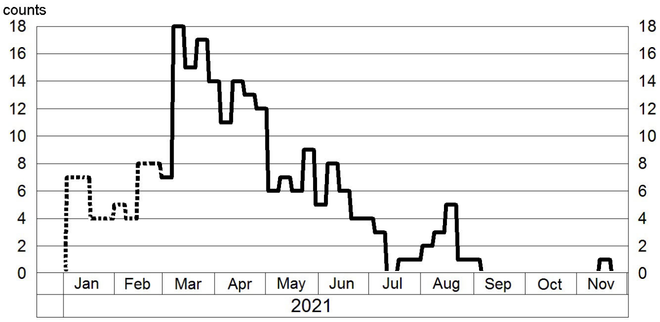

Fig. 4. Parameters of the Earth-Sun-Jupiter configuration during the mutual phenomena of the Galilean satellites in 2021: number of phenomena per week (Monday to Sunday), the dashed sectors correspond to unobservable phenomena.

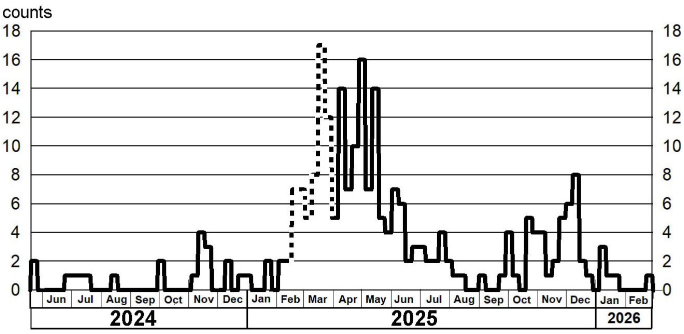

Fig. 5. Parameters of the Earth-Sun-Saturn configuration during the mutual phenomena of the main satellites in 2024-2026: number of phenomena per week (Monday to Sunday), the dashed sectors correspond to unobservable phenomena.

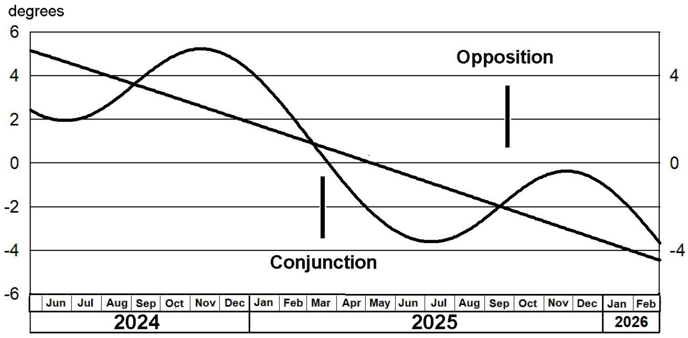

Fig. 6. Parameters of the Earth-Sun-Saturn configuration during the mutual phenomena of the main satellites in 2024-2026: planetocentric planetoequatorial latitudes (deg) of the Earth and the Sun.

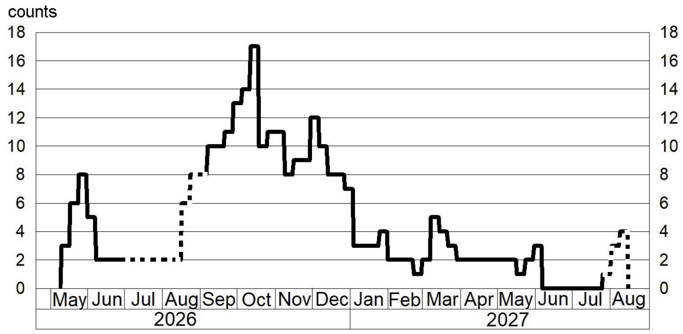

Fig. 7. Parameters of the Earth-Sun-Jupiter configuration during the mutual phenomena of the Galilean satellites in 2026-2027: number of phenomena per week (Monday to Sunday), the dashed sectors correspond to unobservable phenomena.

4.2. *Saturn 2025*

For the satellites of Saturn, the next season corresponds to the next equinox on Saturn occurring on May 7, 2025 since the opposition will take place on September 21, 2025. 137 days separates both dates and the observations will be easier during this interval of time. The total number of phenomena is 249 occurring from 20 May 2024 to 24 February 2026. In fact, only 193 phenomena are observable from 20 May 2024 to 14 February 2025 and from 1 April 2025 to 24 February 2026 due to the conjunction Sun-planet. This is shown by figures 6. The declination of Saturn will be negative (-9 to -2 degrees) around the time of the equinox making the observations easier in the Southern Hemisphere. Figure 5 provides statistics on the distribution of the phenomena during this season.

4.3. *Jupiter 2026-2027*

For the satellites of Jupiter (Galilean and inner satellites), the next mutual phenomenon season after 2021 corresponds to the next equinox on Jupiter occurring on December 16, 2026 since the opposition will take place on February 11, 2027. 57 days separates both dates and the observations will be easy, occurring around the opposition. The total number of phenomena is 305 occurring from May 11, 2026 to August 10, 2027. In fact, only 269 phenomena are observable from May 11, 2026 to June 29, 2026 and from September 1, 2026 to June 6, 2027 due to the conjunction Sun-planet. This is shown by figures 8. The declination of Jupiter will be positive (+8 to +10 degrees) around the time of the equinox making the observations easier in the Northern Hemisphere. Figure 7 provides statistics on the repartition of the phenomena during this occurrence.

The inner satellites will be eclipsed by the Galileans: 316 phenomena will be observable from May 16 to June 28, 2026, and from September 2, 2026 to July 13, 2027. Figure 9 provides statistics on the repartition of the phenomena during this occurrence.

4.4. *The predictions*

For the three occurrences described above, the predictions of all the mutual occultations and eclipses are available though our Multisat ephemerides software provided on the following web page:
http://nsdb.imcce.fr/multisat/nssephme.htm.

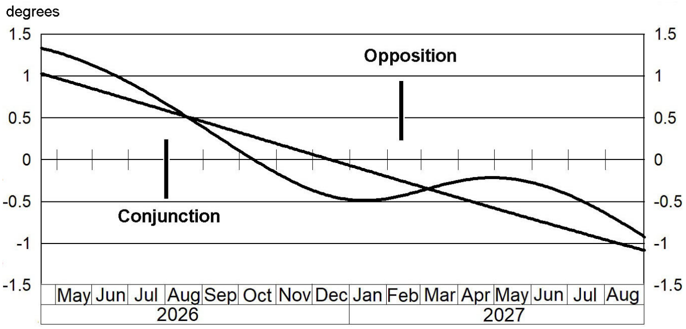

Fig. 8. Parameters of the Earth-Sun-Jupiter configuration during the mutual phenomena of the Galilean satellites in 2026-2027: planetocentric planetoequatorial latitudes (deg) of the Earth and the Sun.

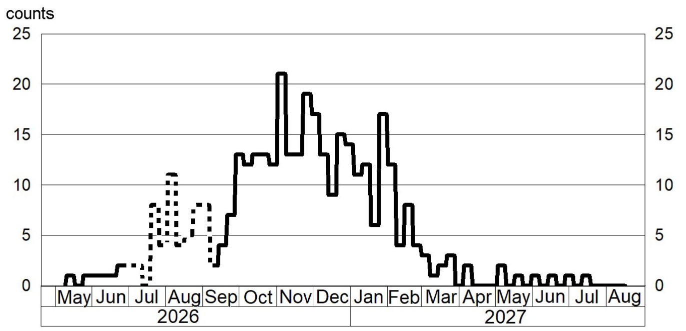

Fig. 9. Parameters of the Earth-Sun-Jupiter configuration during the eclipses of the Inner Jovian satellites in 2026-2027: number of phenomena per week (Monday to Sunday), the dashed sectors correspond to unobservable phenomena.

Thanks to this software, we may know all the phenomena observable for any interval of time and for any observing site (described by its IAU number; if 500 -center of the Earth-all phenomena are provided). For each phenomenon the software provides the date (beginning and end of the phenomenon), the type of phenomenon (which satellite eclipses or occults which satellite), the duration of the phenomenon, the impact parameter (if 1, no phenomenon, if 0, total or central phenomenon), the combined magnitude of the pair of satellites in the phenomenon, the magnitude drop at the maximum of the phenomenon, the distance to the limb of the planet, the distance between the two satellite in case of an eclipse, the elevation of the planet above the horizon, the elevation of the Sun below the horizon and the phase of the Moon (at the date of the phenomenon). Note that we do not provide phenomena with an impact parameter 1 since it does not exist but the phenomena with an impact parameter near 1 are grazing phenomena.

The predictions have been calculated using the ephemerides server Multisat (Emel'yanov and Arlot, 2008) with the satellite motion model by Lainey et al. (2009). Predictions may change if another model is used. Calculations should be remade in the future to take into account the improvement of the ephemerides.

4.5. *Recommendations to observers*

In order to prepare for observations, you might use the help of the Multisat ephemerides which show the configuration of the satellites. If the field is inverted due to the optical design, you must be sure to identify which satellite will be occulted or eclipsed. The predictions provide a start date for the phenomena: start the recording at least 5 minutes before the proposed beginning date and more for long phenomena (most of the phenomena are 5 to 15 minutes long). You should stop the recording at least 5 minutes after the end of the phenomenon. We need to have a sufficient photometry of the satellites outside the time of the phenomenon in order to have a good "zero point" necessary for the photometric reduction, one before the phenomenon and one after. The prediction of the mutual phenomena is very sensitive to the ephemerides. Even though our dynamical model used for the predictions is the most accurate presently available, there is an uncertainty on the ephemerides which may be amplified for phenomena occurring at elongation from the planet. For long phenomena, the elevation of the planet above the horizon may change; same, the Sun may rise during a long phenomenon: caution when observing. Note that our predictions are proposed in UTC but are made in TT. We know the difference between TT and UTC until now but it remains an uncertainty of several seconds of time for 2021, 2025 and 2027.

As we saw above, the Galilean satellites are very bright and a very small telescope (down to 6cm-aperture!) is sufficient to record the mutual phenomena. However, the stability of the instrument and the guiding are fundamental to record reliable data. A CCD camera, a web-cam or even a camcorder placed in the focus of the instrument are suitable: caution, the gain of the camera should not be automatic but fixed during the observation: the photometric reduction requires knowledge of the zero-level of the signal. Images must be saved uncompressed. Each image must be dated in universal time (UTC) to at least 0.1 second of time: the computer internal clock is not sufficiently accurate: GPS time is accurate enough but needs a special receiver. Note that the time stamping of the observation is essential: if the timing is not reliable, the observation will be rejected. If your clock is not sufficiently well synchronized with UTC, note the difference to UTC at the beginning of the observation and also at the end.

Some observers have attempted to observe mutual phenomena during daylight: this is possible for the Galileans using an infra red filter in the methane band (890 nm). However, the sky background remains bright and the seeing is quite bad. An observing site at a high altitude is better for that purpose. Note that a narrow band filter will attenuate the scattered light of the central body: this will improve the SNR. Such a filter is necessary for eclipses of the inner satellites of Jupiter but also for phenomena of the main satellites occurring close to the primary. Then, more phenomena will be observable. In that case a larger telescope is needed.

More information on the observation and the reduction of the mutual phenomena is available on technical notes available at the address: https://www.imcce.fr/recherche/campagnes-observations/phemus/phemu

5. Conclusions

The observation of the mutual phenomena of the natural planetary satellites are performed since the 1970s and have permitted to gather 2391 observations of the Galilean satellites from 1973 to 2015 (42 years), 106 observations of the Saturnian satellites from 1980 to 2009 (29 years) and 41 observations of the Uranian satellites in 2007-2008.

We have seen that the astrometric accuracy of these observations is larger than the one of astrometric direct imaging and is due to two facts:

- the measure of a timing is more precise than the one of a position
- the reduction is calibrated with the size of the satellites in kilometers provided with a high precision by the space probes.

This accuracy has been used by theoreticians who succeeded to extract information from these observations allowing to quantify an acceleration in the motion of the satellites, especially those of Jupiter and Saturn since the interval of time of the observation is sufficiently large.

We encourage further observations to continue improving the quantification of tidal effects which provide constraints on the internal structure of the satellites as demonstrated by Lainey et al. (2009). In order to help these observations, we provide the predictions of the next mutual phenomena for Jupiter and Saturn with tools for observers on the dedicated web site Multisat.

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