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FOUR CENTURIES OF OBSERVATIONS OF THE GALILEAN SATELLITES OF JUPITER: INCREASING THE ASTROMETRIC ACCURACY

J.E. Arlot

IMCCE/Observatoire de Paris, 77 avenue Denfert-Rochereau,
F-75014 Paris, France.
E-mail: jean-eudes.arlot@obspm.fr

Abstract: The main satellites of Jupiter, named Galilean after their discovery by Galileo Galilei, are among the most studied celestial objects. The dynamics of their motions represent one of the most complex challenges in the Solar System but the most interesting, including all the dynamical problems of a gravitational system. The modeling of their motions is difficult because of their size (Ganymede has a size similar to Mars or Mercury) and mutual gravitational perturbations, because of the flatness of Jupiter, the presence of Saturn and the Sun and strong tidal effects between them and the planet Jupiter. However, a good knowledge of their dynamics may help us understand their physical nature (their internal structure influences their motions), their formation and their evolution. For these purposes, accurate astrometric observations are essential to determine the physical parameters of their dynamics. Our purpose in this paper is to explore the history of the progress made in these studies during the last four centuries and the value of using old data in present-day research.

Keywords: Galilean satellites, orbital dynamics, astrometric accuracy

1 INTRODUCTION: THE GALILEAN SATELLITES

The planet Jupiter has a lot of satellites but the Galilean ones are more than simple satellites. Their sizes, similar to small planets such as Mercury or Mars, make them interesting worlds worth exploring. They are bright enough to be observed with small instruments (they would be observable with the naked-eye if Jupiter were not so dazzling). This is why they were observed as soon as a telescope was used to look at Jupiter. The motion of the Galilean satellites seems at first to be very easy to understand: quasi coplanar and quasi circular motions around Jupiter. The first satellite, Io is 422 000 km from Jupiter (as the Moon is from the Earth) but the duration of a revolution around the planet is only 1.77 day (due to the large mass of Jupiter). The second satellite, Europa, is 671 000 km from Jupiter, and has a period of revolution of 3.55 days; the third satellite, Ganymede, is 1 070 000 km from Jupiter, and has a period of revolution of 7.15 days; and the fourth satellite, Callisto, is 1 883 000 km from Jupiter, and has a period of revolution of 16.69 days. Because of the gravitational interactions between the satellites, the longitudes of the first three satellites are linked through the relationship $l_1 - 3\, l_2 + 2\, l_3 = 180° + L_i$, known as the resonance between their motions. L_i is a small quantity named 'libration', showing that the satellites are not exactly in resonance. In fact, the orbits are not exactly circular and in the same plane, and studies of the dynamics of the satellites help us try to understand how their motion is evolving with time (are they going out of resonance?) and aids the exploration of these satellites in complement to space probes visiting the Jovian system. The other satellites of Jupiter are very small, and are either inside the orbit of Io, near the faint rings around the planet, or outside the orbit of Callisto at more than 10 million kilometers from Jupiter. Consequently, their influence on the Galilean satellites is negligible.

From their discovery until today, our understanding of the dynamics of the Galilean satellites has made it necessary to fit their dynamical parameters with astrometric observations of their positions. The accuracy of these observations is crucial and should be homogeneous with the accuracy of the theoretical model. So, the goal of the observers is to get more and more precise data: a new digit in accuracy means the discovery of a new faint effect, gravitational or otherwise, on the motion of the satellites, the signature of a previously unknown character of the satellites. Let us now see how the accuracy of the observations improved year after year, thereby bringing new information about the Galilean satellite system, and how old observations can still be useful for today's studies.

2 THE OBSERVATIONS

First of all, how to estimate the accuracy of the data since many different types of observations were performed? What are astrometric observations? They correspond to the measurement of the positions of the satellites at a given moment, (e.g. see Figure 1) on a given date referred to a common time scale and a well-defined reference frame. Then, the observation will fit the theoretical models of their motions and provide the dynamical parameters of these motions. It is easy to understand that accurate observations will provide accurate parameters. Moreover, bad models will deviate from the observations, showing the defects in these models. Only accurate observations will allow us to detect and correct the errors in the theoretical models.

The first way to get astrometric positions is to measure the celestial coordinates (right ascension and declination of the satellites). These observations are made thanks to micrometric measures, photographic plates, transit circle observations and now CCD images. These measurements are made in geocentric angle units with an uncertainty decreasing with more numerous observations, according to statistical laws.

The second way is to get positions of the satellites relative to the planet Jupiter or to other satellites since the system may be considered as astrometrically isolated. Separation and position angles or tangential coordinates are then obtained in geocentric angle units, as previously. These measurements are made using photographic plates, micrometric or heliometric observations, and now CCD images.

The third way is to have access to relative positions in kilometers in space. This is possible thanks to the space probes making measurements and also thanks to the observation of specific phenomena (mutual occultations and eclipses) involving the sizes of the satellites, which are well known nowadays thanks to space probes.

The fourth way is to get positions from the observations of phenomena such as eclipses or occultations by Jupiter. The geometry of these events is known from geocentric observations and the data obtained are the timings of these events. The uncertainty is then in seconds of time, smaller than the uncertainty in angles since timings are easier to measure than angles. This method is the oldest one since it is also the easiest.

We will analyze the different observations made since Galileo and compare their accuracies. In order to have comparable data, we will express them in angle units (arcsec), in seconds of time and in kilometers. We will convert the original data given in a specific unit (colour-coded in the tables) into the other units just for comparison. One arcsec corresponds to about 3 000 kilometers (at the mean distance of Jupiter) and one second of time to 18 km for Io, 14 km for Europa, 11 km for Ganymede and 8 km for Callisto (average 13 kilometers for all satellites together along the orbits). The values will be either in the tangential plane or along the orbits.

We will estimate the accuracy of the observations through two datasets: first the dispersion of the residuals (r.m.s. or standard deviation) around their mean value, and second, the mean residuals (O-C for positions or C-O for timings). For the calculation of these residuals, we must use the best ephemeris that fits the associated observations, in order to avoid the errors on the theoretical model used for the ephemerides. This best ephemeris to be used can be an old one well fitted to the observations, rather than a recent one that does not fit these observations. The dispersion is, of course, an estimate of the accuracy, but the mean residual may indicate some bias in the observations. The observations must be used as plain individual observations, not normal points issued from several datasets, to be sure that all the observations are comparable.

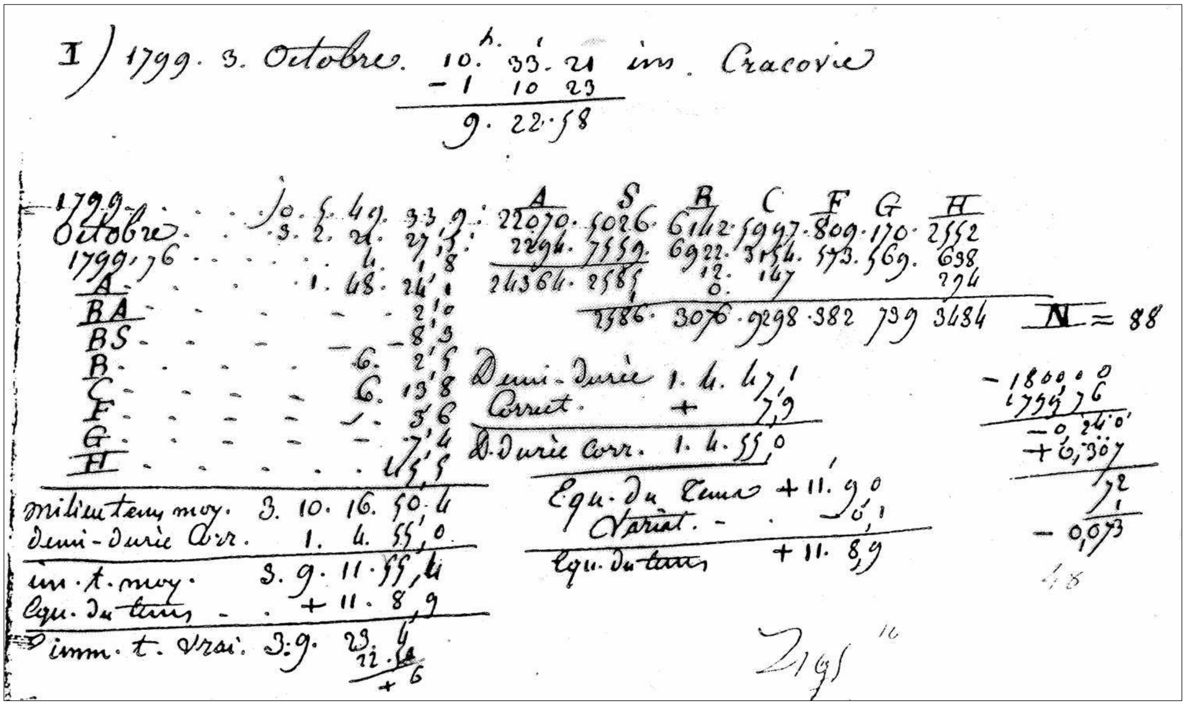

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Figure 1: Delambre's calculation of the position of Io, based on an eclipse that he observed on 3 October 1799.

2.1 The Seventeenth Century: The First Observations

As soon as the satellites were discovered by Galileo Galilei, the first goal was to identify them and to be able to predict their positions in the near future. Galileo immediately thought that the motions of the satellites were so regular that they could be used as a universal clock (or more precisely as a reference for clocks) observable by everyone everywhere and so could be used to determine geographical longitudes (which was a crucial challenge at that time). In order to make even a very simple model it was necessary to make astrometric observations of the positions of the satellites as a function on time. The first measurements were made by Galileo in January 1610: he noted the dates of his observations in ‘hours after sunset’ and he angular measured distances between the satellites or between a satellite and the planet (Galileo, 1610; 1880).

Table 1 provides the (O-C)s and dispersion of these observations using recent ephemerides (old ephemerides are not useful for this). The dispersion of the residuals is about one arc minute, too large to make these observations useful for modern studies. One arc minute corresponds to 180 000 km in space, half the semi-major axis of Io’s orbit and more than twice the diameter of Jupiter. Note that in all of the following tables we will use coloured print to show the astrometric accuracy in the unit used by the observer (seconds of time for events, angles for positions or distances and kilometers for events or space probes measures), but we also will provide the same value in the other units for comparison (using the mean velocity of the satellites as 13 km/s and the angle at mean distance as one arcsec for 3 000 km *in situ*). The accuracy of these observations was bad because of Galileo’s observing method: he estimated distances using the size of Jupiter as his only reference.

In 1612, Galileo understood the phenomena of the eclipses of the satellites in the shadow of Jupiter. These eclipses occur very often, for each revolution of a satellite around the planet, so they are easily observable. Everyone can understand that an observation of an eclipse of a satellite corresponds to an observation of a position of the satellite in its orbit around Jupiter providing the size of the planet is known or taken as a reference unit. The observations of eclipses (the timing of the disappearance and/or reappearance of the satellite in the shadow) were the only way to build ephemerides predicting the positions of the satellites. The accuracy of such observations can be very good. Determining the time of an eclipse with an accuracy of 30 seconds of time, corresponds to accuracy in orbital position of 600 km for Io to 300 km for Callisto, according to the velocities of the satellites. In fact, the timing of an eclipse depended of the sensitivity of the telescope used. For small telescopes, the disappearance of the satellite occurred earlier than in a larger telescope because the image of Jupiter is more blurred. The error in the time of disappearance was supposed to compensate for the error in the reappearance, but the absorption of the air mass and the sky background (twilight …) induced biases. This error will be reduced at the end of the nineteenth century when photometric methods using references were introduced. The true disappearance of the satellites was then better determined since the photometric method helped to determine the true zero photometric value of the signal. Eclipses have been extensively observed since Galileo’s time, and the observations are still used for dynamical purpose. The accuracy of such observations made during the seventeenth century is given in Table 2. In preparing this table we se-

Table 1: (O-C)s for Galileo’s Measurements of Distances: The Dispersion of these Observations is about One Arcmin.

Date (1610)	Hour	Distance	Observation	(O-C)		
				In Time	Angle	km
1 February	18h 19s	Jupiter-Ganymede	6′ 00″	4h 33m	1′ 00″	180 000
		Jupiter-Io	0′ 20″	1h 23m	0′ 30″	90 000
		Jupiter-Callisto	8′ 00″	3h 07m	0′ 30″	90 000
2 February	17h 20s	Jupiter-Ganymede	6′ 00″	6h 49m	1′ 30″	270 000
		Jupiter-Europa	4′ 00″	2h 41m	0′ 45″	135 000
		Europa-Callisto	8′ 00″	9h 05m	2′ 00″	360 000
	23h 20s	Ganymede-Io	4′ 00″	5h 45m	1′ 40″	300 000
		Jupiter-Io	1′ 40″	0h 42m	0′ 15″	45 000
		Jupiter-Europa	6′ 00″	9h 49m	2′ 45″	495 000
		Europa-Callisto	8′ 00″	6h 49m	1′ 30″	270 000
3 February	23h 20s	Jupiter-Europa	1′ 30″	0h 14m	0′ 04″	12 000
		Jupiter-Io	2′ 00″	0h 14m	0′ 05″	15 000
		Io-Callisto	10′ 00″	12h 49m	3′ 20″	600 000

Table 2: Accuracy of the Observations of Eclipses of Io during the Seventeenth Century: Dispersion σ and Mean (C-O).

Author	Opposition	n	Dispersion σ			Mean (C-O)		
			sec	″	km	sec	″	km
Pingré	1652–1654	23	1361	6.85	20565	857	4.28	12855
Pingré	1655	16	196	0.98	2940	64	0.32	960
Pingré	1671	12	89	0.46	1365	–36	–0.18	–540
Roemer	1672–1673	69	62	0.31	930	12	0.06	180

lected several samples of observations from the NSDC database (Arlot and Emelyanov, 2009), with the residuals being taken from the catalogue of eclipses (Lieske, 1986) and extracted from Pingré's compilation of old data (Pingré, 1756; cf. Bigourdan, 1901).

It is easy to see that the observers made progresses in their observing methods year after year.

2.2 The First Tables: The Inequalities from Empirical Tables to Dynamical Theories

The first observers of the motion of the Galilean satellites thought that they were seeing perfectly regular uniform motion, with the satellites orbiting in circular orbits. If this were true, the prediction of the positions would have been easy, but the first tables—calculated by Galileo in 1612 and by Mayr in 1614—appeared to be very inaccurate. The eclipses did not occur regularly: sometimes they were in advance, and at other times late. Why? The cause was what we will call 'inequalities'. The challenge was to observe, explain and understand these inequalities. Before Newton and universal gravitation, the modelling of the motions was purely kinematic. The motions were supposed to be periodic and the modelling was just describing the periodicities. Anyway, it was necessary to make observations with a sufficient accuracy to detect the changes in the uniform revolution of the satellites. Let us see the influence of these 'inequalities' on the motion of the Galilean satellites. Note that the magnitude of the inequalities introduced in the modelling of the satellites' motion must be in accord with the astrometric accuracy of the observations. If the motion of the satellites differs by one minute from the uniform circular motion, observations accurate to 10 minutes will not be able to quantify a one-minute inequality. We must have a minimum accuracy for the astrometric observations in order to be able to shed light on the discrepancy between the ephemerides and the observations. Another question will rise soon: are the satellites accelerating on their orbits? In other words, how can we discriminate between periodic and secular inequalities? We will return to this question later.

The first main cause of inequality in the occurrence of the eclipses was the speed of light. At first, the speed of light was supposed to be infinite but the observation of successive eclipses of Io by Roemer and his colleagues in Paris Observatory demonstrated in 1676 that this was not true (see Bobis and Lequeux, 2008). Because of the motion of the Earth around the Sun, the Earth-Jupiter distance was changing throughout the year: it was smaller at the Sun-Jupiter opposition and larger at the conjunction. The difference was about one astronomical unit (au) between opposition and quadrature and two aus between opposition and conjunction. This delayed the occurrence of the eclipses by about 8 minutes of time between opposition and quadrature, a quantity that was easily observable even during the seventeenth century. Moreover, the eccentricity of the orbit of Jupiter changed the mean Earth-Jupiter distance and had a similar effect with a period of 12 years. These inequalities were not due to dynamical causes, but others were dynamical. As Lagrange demonstrated, most of the motions in the Solar System were two-body problem with perturbations by other bodies implying a variation in the constants of the elliptical orbits. This is the cause of the dynamical inequalities.

Let us examine the different causes of the inequalities (see Table 3):

(1) The N-body problem is the main cause of inequalities: the attraction by other satellites is not negligible and they have a large influence on each other. The influence of Saturn and other planets may be taken into account. The deviation from positions in a uniform motion may reach more than 6 000 km (the maximum for Europa).

(2) The oblateness of Jupiter (J2) has an influence on the motion of the nodes, especially for Europa, with a deviation reaching 2 700 km.

(3) The Sun has an influence, especially on the longitude of Callisto, and the deviation may reach 1 000 km.

(4) Tides from Jupiter: the satellites have sufficient strength to dissipate energy and modify their motion (secular acceleration), and this may induce a deviation of 300 km on Ganymede, accumulated during several tens of years.

(5) The precession of Jupiter has a small influence, and creates a deviation of few tenths of kilometers.

(6) The oblateness of the satellites themselves induces a deviation of a few kilometers

(7) Relativistic effects are very small, and near to Jupiter they correspond to sub-kilometric effects.

Table 3: The maximum deviation induced by perturbations (Lainey et al., 2001).

Deviation	N-body Problem	J2 Jupiter	Sun	Saturn	Tides Over One Century	Jovian Precession	J2 Satellites	Relativistic Effects
in km	6282 (Europa)	2712 (Europa)	1052 (Callisto)	226 (Callisto)	300 (Ganymede)	80	5	2 (Io)
in arcsec	2	0.9	0.35	0.075	0.10	0.027	0.002	<0.001
in sec	449	194	131	28	27	10	0.6	0.12

Starting from Galileo, the importance of the eclipses of the Galilean satellites (useful for the determination of longitudes) encouraged the prediction of these events and the construction of tables of the movement of these bodies. The first tables by Galileo, Marius, Hodierna and Borelli were not good since they did not take the speed of light into account. The approach of the problem was purely kinematic. In 1668 Cassini published his "Tables of the movement and calculation of eclipses". In 1690, tables for the eclipses of Io appeared in the *Connaissance des temps* based upon better tables by Cassini, and they were improved further by Maraldi in 1730. In 1749, Bradley published tables and noticed an inequality of 437 days in the eclipse times of the first three satellites. Maraldi pointed out at this date the mutual action of the satellites and one began to be suspicious about the eccentricities of the orbits and the nature of the inequalities. Wargentin published improved tables in 1757. At this time, the movement of the satellites was still expressed in the form of kinematic empirical equations, and Lalande could say in the *Connaissance des temps* for 1763 that "… the inclinations and the nodes of the orbits have variations that are still poorly known."

In the eighteenth century, from Newton to Laplace, the principles of dynamics and universal gravitation were put in place, and everything changed in the modelling of motions: it became possible to write equations representing dynamic models. For the Galilean satellites, the problem was very difficult as many forces acted on the satellites: the Sun, far away but massive; the flattening of Jupiter; the planet Saturn; and also the mutual interactions between the satellites. From these interactions would result a resonance that would force the motion of satellites. The first three satellites did not move independently of each other, but their longitudes, L_1, L_2 and L_3, were linked by the relation $L_1 - 3 L_2 + 2 L_3 = 180°$.

Satellites obviously tend to escape this constraint, creating more 'inequality', but they cannot move away from it by more than one degree: the resonance brings them back to their imposed configuration.

From the dynamic equations, the tables (or ephemerides) progressed quickly: the first theories were due to Bailly and Lagrange in 1766, then came that of Laplace, the most complete in 1788. In 1791, Delambre built tables from Laplace's theory and from the analysis of more than 6 000 eclipses.

The nineteenth century was the 'golden age' of celestial mechanics and astrometric observation. From the theoretical point of view, Damoiseau improved on Laplace's work in order to publish ephemerides and predictions of eclipses with a better precision. Further improvements were made by Souillart in 1880. Then followed the monumental work of Sampson, who developed a complete analytical theory of the motion of the Galilean satellites, a theory that was used to build the ephemerides at the end of the nineteenth century but because of the complexity of the task was not published until 1921. Ephemerides were based upon this theoretical model until the end of the twentieth century. Today, computers allow us to build purely numerical solutions that are easier to obtain and include all the inequalities.

2.3 The Publication of the Tables in the *Connaissance des temps*

The *Connaissance des temps* contained the first published ephemerides, starting in 1679. Because of the strategic use of the Galilean satellites for the determination of longitudes, efforts were made in France by Colbert and Louis XIV to promote astronomy at the newly built Paris Observatory. The first ephemerides of the Galilean satellites were, in fact, only the predictions of the eclipses of Io, starting in 1690 when one became more confident in the ephemerides. Table 4 below shows the evolution of the ephemerides. Publishing eclipses or phenomena is easy: it is a list of events with precise dates. Publishing positions is much more difficult because of the high velocity of the satellites. Publishing positions hourly would take pages and pages, so that positions—useful to identify the satellites—were first published under the form of isolated points day after day, allowing the user to interpolate the position of the satellites. Latter, the points were replaced by curves. Such a representation was sufficient since the accuracy of the observations was poor but, in order to calculate (O-C)s with better observations, ephemerides have been improved. Elements used with short calculations were published giving better positions. After 1980, thanks to the arrival of electronic calculators, a representation under the form of mixed functions and latter under the form of Chebychev polynomials was provided as ephemerides. Note that the ephemerides must have a precision in agreement with that of the observation (actually they are presently one order of magnitude better).

Nowadays, the ephemerides are available through the Internet, either directly in the form of positions or in the form of coefficients. The present *Connaissance des temps* contains positions at elongations for checking of the theoretical models used for the ephemerides.

Table 4 summarizes the progresses in the ephemerides.

Table 4: Evolution of the ephemerides of the Galilean satellites of Jupiter.

Dates	Positions	Phenomena	Configurations	Theoretical Model From
1679–1689	--	--	--	--
1690–1693	--	Eclipses of Io	--	Cassini
1694–1697	--	--	--	--
1698–1729	--	Eclipses of Io	--	Cassini
1730–1733	--	Eclipses of the 4 satellites	--	Maraldi
1734	--	Eclipses of Io	--	Maraldi
1735–1762	--	Eclipses of the 4 satellites	Points each day	Maraldi
1763–1765	Daily and hourly elements	Idem	Idem	Idem
1766–1807	Idem	Idem	Idem	Wargentin-Lalande
1808–1840	Idem	Idem	Idem	Delambre
1841–1880	Idem	Idem	Idem	Damoiseau
1881–1890	Elements	Idem	Idem	Souillart
1891–1914	Idem	All phenomena for the 4 satellites	Idem	Idem
1915–1960	Idem	Idem	Idem	Sampson-Schulhof
1961–1979	Idem	Idem	Curves	Idem
1980–1984	Chebychev polynomials	Idem in a supplement	Idem in supplement	Sampson-Arlot
1985–1995	Mixed functions	Idem	Idem	Idem
1996–2005	Idem	Under the form coefficients	Idem	Idem
2006–2007	Positions at elongation	Idem	Idem	Idem
2008–Today	Idem	Idem	Idem	Lainey

Table 5: Accuracy of the observations of Delambre's eclipses made at the end of the eighteenth century (1775–1802): Dispersion σ and Mean (C-O).

				Dispersion σ			Mean (C-O)		
Obs. Sites	Events	n	Ephemeris	sec	(″)	km	sec	(″)	km
All	Immersion & Emersion	845	Delambre	42	0.18	546	3	0.01	39
			E2	64	0.28	832	–19	–0.08	–247
	Immersion	360	Delambre	39	0.17	507	20	0.09	260
			E2	39	0.17	507	40	0.17	520
	Emersion	485	Delambre	39	0.17	507	–10	–0.04	–130
			E2	39	0.17	507	–63	–0.27	–819
Paris	Immersion & Emersion	160	Delambre	28	0.12	364	6	0.03	78
			E2	44	0.19	572	–13	–0.06	–169
Viviers	Immersion & Emersion	98	Delambre	57	0.25	741	7	0.03	91
			E2	84	0.36	1092	–16	–0.07	–208
Greenwich	Immersion & Emersion	78	Delambre	24	0.10	312	12	0.05	156
			E2	47	0.20	611	–5	–0.02	–65
Prague	Immersion & Emersion	67	Delambre	52	0.23	676	1	0.00	13
			E2	73	0.32	949	–27	–0.12	–351

2.4 The Observation of Eclipses: Eighteenth and Nineteenth Centuries

As seen in Table 1, the observations of positions were not good during the first epochs of observation of the Galilean satellites, so that mainly eclipses (and also some occultations of the satellites by the disc of the planet) were observed. Eclipses were extensively observed in order to be able to build accurate predictions of future ones. These events were used for the determination of the geographic longitudes. The method was to observe the same event from two different sites. The comparison of the local true solar times of the eclipse provided the difference in the longitudes of the two sites, but one had to carry the information from one site to the other before obtaining the result. But for a traveler who needed to know his longitude immediately the use of the eclipses was different: he had to have at hand the *Connaissance des temps* to know when the next eclipse would occur and at what time in Paris, then the observed local time of the eclipse directly provided the longitude of the observing site with reference to the longitude of Paris Observatory. In that case, the accuracy of the prediction was critical.

Many observing campaigns were organized to determine longitudes and improve the prediction of eclipses: for example, Figure 1 shows the reduction of an observation made in 1799 at Cracovie (Krakow) in Poland, while in Table 5 we present the accuracy of the sets of eclipses gathered by Delisle and Delambre (after Arlot et al., 1984).

After the end of the eighteenth century, the modelling of the motion of the satellites was no more kinematic: celestial mechanics came into the picture, thanks mostly to Laplace, and the motions were described through dynamical equations. Then, the observations were not made in order to describe the motion but to provide the constants of integration in the equations of the motion or the initial conditions of this motion. In theory, only one observation of position and velocity of each satellite was sufficient, supposing that the accuracy of the measurement was infin-

Table 6: Accuracy of the observations of Pickering-Sampson's nineteenth century eclipses, where the Dispersion σ and Mean (C-O) refer to the E2 ephemeris.

		Dispersion σ			Mean (C-O)		
opposition	n	s	(″)	km	s	(″)	km
1893–1894	95	58	0.25	754	–2	–0.01	–26
1899	61	45	0.20	585	–2	–0.01	–26
1901	32	34	0.15	442	–5	–0.02	–65

ite and supposing that all the gravitational and non-gravitational effects were included in the equations of the motion. In practice, a large number of observations was still necessary in order to increase the accuracy of the observational measures and to be able to detect the forgotten forces affecting the motion in the residuals. This explains the efforts of Delambre to gather numerous accurate observations of eclipses in order to prepare ephemerides using the Laplace's equations. Table 5 shows how the accuracy of the observations increased when compared to the seventeenth century observations given in Table 2.

At the end of the nineteenth century, the observations of eclipses took advantage of progress in observational techniques. One of the main difficulties of the eclipse observations was to determine the zero light level after the beginning of an eclipse or before its end. As we have seen, this level occurred apparently earlier with less sensitive telescopes. This was a problem during the seventeenth century. Delambre understood that it was necessary to model the shadow cone and to time an eclipse at the instant where the center of the satellite was on the shadow cone. However, some biases in his model were corrected by his dynamical model of motion that explaining his very small residuals (the mean C-O in Table 5) compared to the larger residuals for more recent theories and observations that did not include Delambre's biases. During the 1870's Pickering at Harvard started photometric observations of the eclipses. For these observations, a model of theoretical light curves was used in order to have some absolute measurements of the light fluxes coming from the satellites (Sampson, 1909). This allowed the accuracy of the eclipse observations to increase (cf. Table 6), and Sampson (1910; 1921) mainly based his new theory of the motion of the Galilean satellites on these eclipses due to their better accuracy.

2.5 The Nineteenth Century: Back to the Direct Observation of Positions

The increase in size of the telescopes and the improved longitudes of the observatories (providing a better timing) allowed increasing accuracy of the observations of the Jovian eclipses. However, it appeared that the results were limited by the number of actually observed eclipses (eclipses can occur when Jupiter is not observable or when the sky is cloudy) and by the fact that no observation was made of the elongation of the satellites. It was time to come back to observations of direct astrometric positions, as Galileo did, in order to have data covering more regularly the orbits of the satellites. Bessel (1841-1842) suggested using micrometers or heliometers to make these measurements. They comprised measuring the angular distances and position angles between the satellites or between a satellite and Jupiter, as shown by Figure 2.

Bessel used a Fraunhofer heliometer starting in 1838. This instrument was first built in order to measure the diameter of the Sun but was well adapted to the Galilean satellites. These objects were sufficiently bright, of the same brightness and not too far from (and not too close to) each other. The heliometer consisted in a lens cut down the middle whose two halves could move along their common side (see Figure 3). The observer had to superimpose the two images made by the two half-lenses and then to measure the distance between the two half-lenses. A rotation of the system provided the position angle. Observations of reference stars were necessary to calibrate the distance between the half-lenses. It was also necessary to take refraction into account. The astrometric accuracy of such measurements was amazing.

Bessel made many observations of positions of the Galilean satellites in order to determine the mass of Jupiter. The dispersion of the measures may be estimated at 0.30 arcsec, but we are unable to calculate mean (O-C) residuals since no ephemeris fitting Bessel's observations exists. After Bessel, heliometers were improved and their aperture increased, such as the one at the Cape Observatory in South Africa, thanks to Sir David Gill (1896).

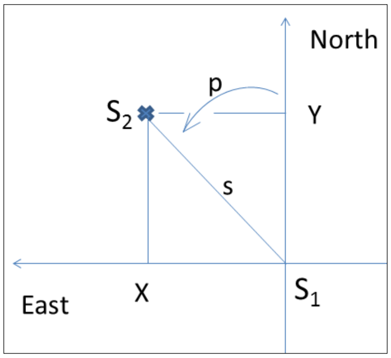

Figure 2: Separation (s) and position angle (p) and corresponding tangential X and Y co-ordinates between two satellites S_1 (reference) and S_2.

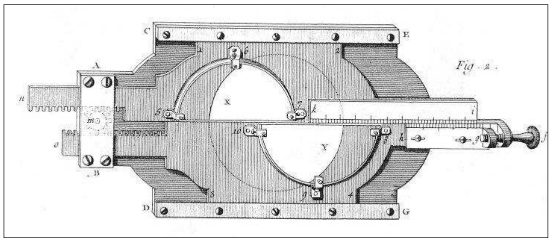

Figure 3: The principle of the heliometer (after Les instruments ..., 1774).

Table 7 provides mean (O-C)s and dispersion of the measurements made with heliometers. It seemed that an increase in aperture and focal length of the heliometers would increase the accuracy but in spite of the wishes of the astronomers no larger heliometers were built.

2.6 The Occultations

Eclipses in the shadow of Jupiter were the most observed phenomena. However, as we saw, astronomers wished to increase the possibility of observations. Observations of the occultations of the satellites by the disk of the planet brought a solution to that problem. It was more difficult to make these observations because the disc of Jupiter is very bright and the limb is not well defined. But with good seeing, the contrast between Jupiter and the satellites was not too large and the observations were accurate. Most such observations were made during the interval 1870–1910 (Fairhead et al., 1986) and Table 8 provides the mean (O-C)s and the dispersions.

2.7 The Photographic Technique

The photographic technique was introduced at the end of the nineteenth century. The innovation was that the observations were recorded and preserved so that their analysis could be made several times in order to exclude systematic or personal errors and to improve the precision of the measurements. As with the micrometric and heliometric observations, the measures were in millimeters and astronomers had to link these measurements to angles and reference frames. The main method for reducing the images and deriving astrometric positions was to use reference stars to link the positions of the satellites to an absolute reference frame. The problem with the Jovian system was that the satellites and Jupiter were very bright and the reference stars very difficult to see on the same plates. A compromise had to reached on the focal length of the telescope. A long focus gave a better astrometric measuring accuracy but a lower sensitivity. However, a short focus telescope presented a larger field for the same size of plate and then more reference stars could be found, allowing a better calibration of the scale (transformation of millimetres into angles). In the case where there was a lack of reference stars, it was possible to determinate the scale using another field that included good reference stars and to record the trail of a star by stopping the diurnal motion of the telescope. This trail provided the equator of the date, allowing a link of the measurements to the reference frame. Table 9 shows the different astrometric accuracies that were obtained by the photographic technique with instruments at various observatories. It is evident that long focus instruments provided a better accuracy than the short focus ones. However, with the recent algorithms of astrometric reduction and the new star catalogues, short focus observations may now reach the same accuracy as the long focus ones.

Table 7: Accuracy of Heliometer Observations: Dispersion σ and Mean (O-C).

			Dispersion σ			Mean (O-C)		
Observers	Opposition	n	sec	(″)	km	sec	(″)	km
Gill	1891	214	35	0.15	450	35	0.15	450
Cookson	1901	171	44	0.19	570	46	0.20	600
Cookson	1902	215	44	0.19	570	39	0.17	510
USNO	1903	149	67	0.29	870	65	0.28	840
USNO	1904	149	67	0.29	870	58	0.25	750
USNO	1905	85	67	0.29	870	53	0.23	690

Table 8: Accuracy of Occultation Observations by the Disk of Jupiter: Dispersion σ and Mean (C-O).

				Dispersion σ			Mean (C-O)		
Observer and Sites	Dates	Satellite	n	sec	(″)	km	sec	(″)	km
R.T.A. Innes (South Africa)	1909	1	84	25	0.15	450	24	0.14	432
		2	38	40	0.19	560	19	0.09	266
		3	36	72	0.26	792	32	0.12	352
		4	8	102	0.27	816	105	0.28	840
J. Tebbutt (Windsor, Australia)	1889	1	65	59	0.35	1062	31	0.19	558
		2	36	63	0.29	882	68	0.32	952
		3	20	178	0.65	1958	198	0.73	2178
		4	5	113	0.30	904	103	0.27	824
All observatories	1836–1972	1	2084	111	0.67	1998	27	0.16	486
		2	1129	165	0.77	2310	54	0.25	756
		3	1009	232	0.85	2552	121	0.44	1331
		4	189	291	0.78	2328	–12	–0.03	–96

Table 9: Accuracy of Photographic Plates Series: Dispersion σ and Mean (O-C).*

					Dispersion σ			Mean (O-C)		
Author	Observing Site	F	Opposition	n	sec	(″)	km	sec	(″)	km
Renz	Helsingfors	3.4	1892–1893	144	62	0.27	800	–12	–0.05	–156
Renz	Pulkovo	3.4	1895–1896	204	55	0.24	720	–6	–0.03	–80
Kostinsky	Pulkovo	3.4	1907–1908	161	78	0.34	1020	24	0.10	310
Chevalier	Zô-Sé	7.1	1917–1918	110	185	0.80	2400	0	0.0	0
De Sitter	Greenwich	6.9	1918–1919	252	85	0.37	1100	–6	–0.03	–80
De Sitter	Capetown	6.9	1924	246	60	0.27	800	–2	–0.01	–26
Petrescu	Bucharest	6.1	1934	54	50	0.22	660	–16	–0.07	–210
Petrescu	Paris	3.4	1936	25	110	0.46	1400	3	0.01	40
Biesbroek	Yerkes	2.3	1962	66	200	0.88	2640	15	0.07	195
Soulié	Bordeaux	3.4	1966–1967	36	83	0.36	1100	–15	–0.07	–195
Pascu	Charlottesville	9.9	1967–1968	95	25	0.11	330	–3	–0.01	–40
Pascu	Washington DC	9.9	1974	123	23	0.10	300	10	0.04	130
Ianna	Charlottesville	9.9	1977–1978	109	37	0.16	480	0	0.0	0

* F= focal length of the telescope in meters; n= number of exposures

One problem to be solved is the brightness of Jupiter, especially if bad seeing is spreading the light of the satellites over a larger area. Moreover, a kind of halo is always around Jupiter, increasing the brightness of the sky background. The challenge was to eliminate this halo, which makes the measurement of the positions of the satellites more difficult and inaccurate. This was solved using masks or filters. Figure 4 shows three different kinds of masks. The mask in Figure 4a was used by Chevalier (1921), a kind of shutter that made it possible to take shorter exposures for the planet than of the satellites. Figure 4b is the system used by Petrescu (1938; 1939): a mask that allowed Jupiter to be exposed in the middle of a photograph of the satellites. Figure 4c is a system of filters developed by Pascu (1977) that were different for Jupiter, for the brightest satellites and for the faintest satellites, and allowed measurable images to be taken with reference stars in the background, thanks to longer exposures.

The interest of these techniques also made it possible to measure the planet Jupiter and the relative positions of the Jovian satellites. However, the use of Jovicentric positions was not used very often since the satellites are orbiting around the center of mass of the Jovian system and not around the center of the planet. Note that no photographic observations or other types of observation of the Galilean satellites were performed during the interval 1920–1970, except for some rare observations. This was due to the fact that the ephemerides were supposed to be perfect after the triumph of celestial mechanics in the nineteenth century. The need for new observations appeared only before the 1970's during the preparation for the space missions. Ephemerides had to be improved for the launch of space probes to the Jovian system.

2.8 The Transit Circle and the Astrolabe

These instruments measured the time of transit of an object on the local meridian of the observing site using a transit circle or at a given elevation using an astrolabe. This timing associated with the measured elevation of the object provides the right ascension and declination of the observed objects as a function of sidereal time. Many such observations were made for building catalogues of reference stars. Since the Galilean satellites are bright, it was possible to observe them with a transit circle. At first the visual observations were not very accurate but the arrival in the 1980s of new CCD detectors used in the TDI scanning mode (continuous readings of the target) introduced a large improvement in the astrometric accuracy. Strips of sky containing the satellites and reference stars were thus observed providing astrometric positions. Table 10 gives the accuracy of transit circle observations made at Bordeaux Observatory during the period 1998–2005 using this technique.

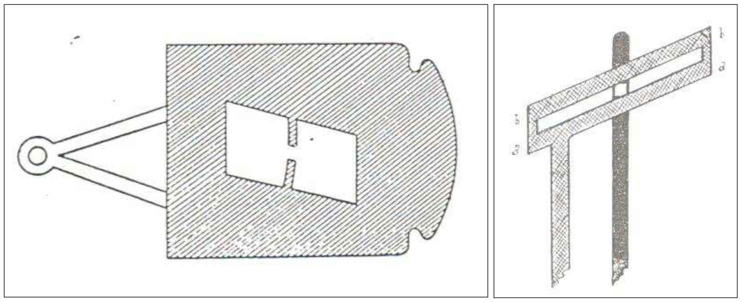

Figure 4: Systems used to decrease the brightness of Jupiter and the satellites on photographic plates. Figure 4a (left): the rotating system used by Chevalier in Zô-Sé; Figure 4b (middle): the system used by Petrescu in Bucharest and Paris; Figure 4c (right): the filtering system used by Pascu in Washington, DC.

Table 10: Accuracy of CCD Transit Circle Observations: Dispersion σ and Mean (O-C).

		Dispersion σ			Mean (O-C)		
Satellite	n	sec	(″)	km	sec	(″)	km
Io (RA)	153	8	0.047	141	–1	–0.007	–21
Io (Dec)	153	7	0.040	120	0	0.002	6
Europa (RA)	167	11	0.050	150	2	0.010	30
Europa (Dec)	167	9	0.044	132	1	0.003	9
Ganymede (RA)	176	16	0.058	174	–1	–0.004	–12
Ganymede (Dec)	176	16	0.055	165	–2	–0.007	–21
Callisto (RA)	188	21	0.055	165	0	0.001	3
Callisto (Dec)	188	16	0.043	129	1	0.002	6

2.9 The End of the Twentieth Century: Back to the Observation of Phenomena for a Better Accuracy

At the end of the twentieth century, the progress made with theoretical models, the observations from space probes and the search for tidal effects on the motion of the Galilean satellites required new accurate ground-based observations in order to complement space observations that were made on very short time intervals and could not detect the astrometric signatures of long-term effects. The first CCDs were difficult to use for the Galilean satellites because of their small field and because of the brightness of the satellites inducing short exposures and a lack of reference stars. CCDs were then useful in order to increase the astrometric accuracy of transit circles but were not able to replace completely the photographic observations. The observers went back to the phenomena: however, the atmosphere of Jupiter was still not modelled and the attention of the observers went to other phenomena of the Galilean satellites: the mutual occultations and eclipses. These events are rarer than the classical occultations and eclipses by Jupiter that occur for each revolution of the satellites: the mutual events occurred only when the Earth (for the occultations) or the Sun (for the eclipses) were in the orbital plane of the satellites (Figure 5).

This configuration corresponds to the equinox on Jupiter (the Sun being in the Jovian equatorial plane which is the orbital plane of the satellites) and occurs every six years. During one year, numerous mutual phenomena are observable. Since the satellites have no atmosphere, the mutual events provide very sharp light curves not affected by any atmosphere and it is easy to go back from the light curve to the relative positions of the two involved satellites with an accuracy not depending on the distance to the observer, i.e. in kilometers through the size of the satellites. The observation consists in the timing of the light curve which will be fitted on a model, allowing to determine the relative positions of the two involved satellites. Table 11 indicates the astrometric accuracy of such observations. We see that the dispersion increases with time: the more recent observations have a larger dispersion since amateur astronomers were involved in the observations while in 1973, only professional photometrists were observing.

These observations began when their predictions were possible, i.e. after the arrival of computers. These events are very sensitive to the relative inclinations of the orbits of the satellites and need complex computations. The first observing campaign took place in 1973, and there were further campaigns that regularly provided a source of very accurate astrometric data.

For the last observing campaigns CCDs were used, providing a series of images. Each image was analyzed and a photometric signal was extracted in order to get the light-curve of the phenomenon. Some observers thought that these ser-

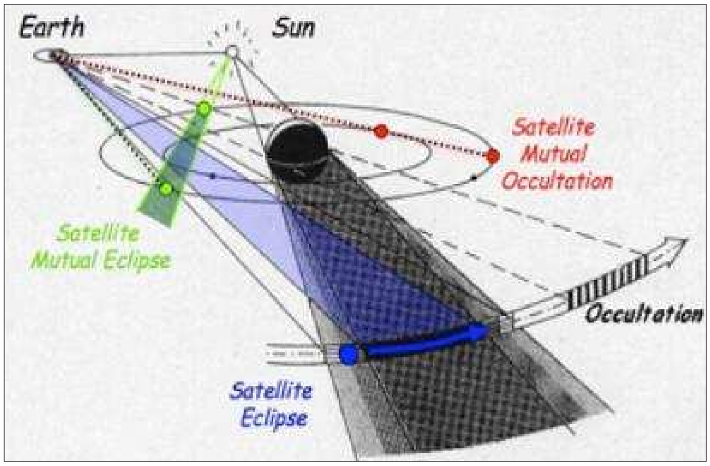

Figure 5: Geometry of the Eclipses and of the Mutual Phenomena of the Jovian Satellites.

Table 11: Accuracy of Observations of Mutual Events: Dispersion σ and Mean (O-C).

			Dispersion σ			(C-O)		
Occurrence	Satellite	n	sec	(″)	km	sec	(″)	km
1973	1	15	3.3	0.020	60	1.0	0.006	18
	2	66	3.0	0.014	42	0.4	0.002	6
1985	1	43	3.7	0.022	66	0.7	0.004	12
	2	92	8.6	0.040	120	1.5	0.007	21
1991	1	148	3.5	0.021	63	2.2	0.013	39
	2	36	7.3	0.034	102	3.9	0.018	54
1997	1	12	15.8	0.095	285	6.3	0.038	114
	3	19	32.7	0.120	360	6.5	0.024	72
2003	1	86	14.7	0.088	264	1.0	0.006	18
	2	114	19.5	0.091	273	2.6	0.012	36

ies of images might be analyzed as astrometric images during the close approach between two satellites independently of the occultation or the eclipse. Moreover, such series of images could be made even when no event was predicted, providing, as for an event, the timing of the minimum separation distance. Very few observers made such observations but Morgado et al. (2016; 2019) published results using this technique. It is too early to make statistics on the accuracy of such a method but the first data are encouraging. In fact, the large number of measured images increases the astrometric accuracy of the measurements. In their second paper, Morgado et al. (2019) announce a combined (C-O) (offset) for all their data of 3.8 mas, i.e. 11 km or 1 second of time and a standard deviation of 2.9 mas, i.e. 9 km or less than one second of time (as shown in Tables 12a and 12b). These results seem to be very good, but they need to be confirmed by more observations. The measurement of the minimum of distance during the close approach should be improved, and will provide better astrometric accuracy.

2.10 New CCD Observations

Let us recall the main problem of the observation of the Galilean satellites: they are too bright. This explains that we have more observations of the Saturnian system than of Jupiter even if the Galilean satellites were observed earlier. The arrival of the CCDs was not at first a progress for the Galileans. Using photographic plates, several devices were necessary in order to decrease their brightness allowing stars to be observed in the same field. The small CCDs were not adapted for this method. However, the progress of the CCDs, their increase in size, in sensitivity and in rapidity of reading the pixels allowed astronomers to stack many images made with short time exposures. The Galilean satellites were overexposed and stars were visible on the images. The sum of all images allowed us to have well-measurable objects. Table 13 (after Lainey et al., 2017) shows the (O-C)s and the dispersion of the observations obtained with large CCDs.

2.11 Observations From Space

2.11.1 *Voyager Space Probe*

The space probes used accurate ephemerides for their navigation to Jupiter but, once on site, they were able to provide astrometric observations of the satellites. The Voyager space probes came very close to the satellites so that one arcsec as seen by Voyager corresponded to 5 km in space position of the satellites. The accuracy of 10 km corresponds to an accuracy of 3 mas for ground based observations (and to an event accurate to one second of time). The dispersion of space probes observations is 820 mas (milliarcseconds) as seen from the probe, i.e. 3 mas geocentric.

Note that these observations were made during a short interval of time. Even though they are accurate, they do not contain information on long-term residuals and must be complemented

Table 12a: Accuracy of observations of close approaches between satellites: the timings.

	n	Dispersion σ			(C-O)		
		sec	(″)	km	sec	(″)	km
2016	14	5	0.021	63	1.4	0.006	18
2019	104	0.7	0.003	9	0.9	0.004	11

Table 12b: Accuracy of observations of close approaches between satellites: the distances.

	n	Dispersion σ			(O-C)		
		sec	(″)	km	sec	(″)	km
2016	14	7.5	0.032	96	−4.7	−0.020	−60

Table 13: Accuracy of CCD Observations with Stacking Imaging: Dispersion σ and Mean (O-C).

		Dispersion σ			Mean (O-C)		
Sat.	n	sec	(″)	km	sec	(″)	km
Io (RA)	25	3	0.019	57	–1	–0.006	–18
Io (Dec)	25	3	0.017	51	1	0.003	9
Europa (RA)	25	4	0.017	51	0	–0.001	–3
Europa (Dec)	25	3	0.015	45	–2	–0.008	–24
Ganymede (RA)	25	7	0.027	81	5	0.022	66
Ganymede (Dec)	25	6	0.022	66	0	–0.001	–3
Callisto (RA)	25	13	0.035	105	–5	–0.014	–42
Callisto (Dec)	25	9	0.023	69	2	0.006	18

Table 14: Accuracy of HST Astrometric Positions: Dispersion σ and Mean (O-C).

			Dispersion σ			(O-C)		
Satellites		n	sec	(″)	km	sec	(″)	km
Io	RA	32	7.2	0.043	130	–6.8	–0.041	–123
	Dec	32	7.2	0.043	130	8.9	0.053	160
Callisto	RA	10	7.9	0.021	63	0.9	0.002	6
	Dec	10	6.7	0.018	54	5.6	0.015	45

Table 15: Accuracy of newly digitized and re-reduced photographic plates (1986–1990): Dispersion σ and Mean (O-C).

Satellite	n		Dispersion σ			(O-C)		
			sec	(″)	km	sec	(″)	km
Io	333	Right ascension	4.4	0.027	80	–0.3	–0.002	–6
	333	Declination	6.7	0.040	120	1.7	0.010	30
Europa	333	Right ascension	5.0	0.023	70	–0.1	–0.0005	–1.5
	333	Declination	8.6	0.039	120	–1.4	–0.007	–20
Ganymede	355	Right ascension	5.4	0.020	60	0.5	0.002	6
	355	Declination	10.9	0.039	120	0.5	0.002	6
Callisto	369	Right ascension	7.5	0.019	60	–0.1	–0.0002	–0.6
	369	Declination	8.2	0.022	66	–1.5	–0.004	–12

by long series of ground-based observations. Another result from the space probes is the determination of the masses of the satellites during the close approaches between the probes and the satellites. Their masses were easily determined by analyzing the orbital deviation of the space probes during such close approaches (Jacobson, 2013). Finally, the space probes provide accurate values for the sizes of the satellites, which are the basis of the reduction of the observations of mutual phenomena.

2.11.2 Hubble Space Telescope

We must notice also that observations were made from the HST: Table 14 shows the accuracy of HST astrometric positions.

2.12 The Twenty-first Century and the Gaia Revolution: Back to the Old Observations

The effects due to long-term residuals, especially the secular terms, must be determined by long-term series of observations. A new idea was to reduce past observations using today's accuracy, but how to do this? At the beginning of the twenty-first century it became possible to scan and digitize old photographic plates with modern scanners accurate to a few nanometers (Robert et al., 2010) and to reduce them using the new accurate catalogues of reference stars. Many errors made in the past can now be eliminated and accurate positions of the satellites can be derived from observations made many years ago. Table 15 provides the accuracy of positions obtained with the new reduction, and can be compared with Table 9 that shows similar data obtained using old manual reduction techniques.

Table 16 shows the accuracy of several catalogues of reference stars with the dates they were obtained. The astrometric accuracy of these reference stars has a direct consequence on the accuracy of the astrometric reduction of most of the observations of the Galilean satellites. Each time a new more accurate catalogue is published, a new reduction of old observations (photographic plates or CCD) can bring better data for analysis. However, we must notice that the astrometric observations of the Galilean satellites generally give relative positions either between the satellites themselves or between the satellites and Jupiter. The use of right ascension and declination positions started during the twentieth century as soon as the star catalogues allowed

Table 16: Accuracy of Reference Star Catalogues.

Year	Name	Number of stars per square degree	Number of stars	Magnitude limit	Accuracy in mas (0.001 arcsec)
1907	NFK	<1	925		187
1937	FK3	<1	1 535	7	120
1937	GC	1	33 342		214
1975	AGK3	10	181 581	11	215
1963	FK4	<1	1 535	7	98
1966	SAOC	6	258 997		281
1991	PPM	10	378 910		138
1997	Hipparcos	3	100 000	12.4	0.8
1998	USNO A2		526 280 881	20	250
1998	USNO SA2		54 787 624		250
2000	Tycho 2	62	2 500 000	16	60
2001	GSC	500	19 000 000		360
2003	2MASS		470 000 000	16	60–100
2004	UCAC2	1200	48 000 000	7.5–16	20–70
2015	GAIA	25 000	1 billion	20	0.01

such astrometric reductions. The right ascension and declination observations of the satellites allows us to obtain the right ascension and declination positions of the center of mass of the Jovian system and to determine its motion around the Sun.

In 2018, the Gaia astrometric telescope provided its DR2 Reference Catalogue with positions of stars to 0.01 mas. Even better, the DR2 Catalogue will give proper motions of reference stars to an accuracy of one mas per century. As a consequence, the astrometric accuracy of old re-reduced photographic plates will have an accuracy at least at the level of those of Table 16 (around 30 mas) instead of the usual accuracy of several hundreds of mas of the reductions made at the time of the observations. The Gaia DR2 Catalogue opens a new era for the astrometry of the Galilean satellites for which we have photographic plates starting at the end of the nineteenth century.

3 DYNAMICAL MODELS: NEW RESULTS AFTER 400 YEARS OF STUDIES

The need to improve astrometric accuracy was mainly guided by the research on small effects in the residuals. One of these effects that the astronomers were looking for was the tidal effects in the Galilean system. As Jupiter induces tides on the satellites, then, the satellites are moving towards Jupiter, their motions being accelerated because of the dissipation of energy inside the satellites. But as the satellites also induce tides on Jupiter, they lose energy and are flying away from Jupiter (as the Moon does from the Earth). Then astronomers try to find an acceleration in the motion of the satellites, this acceleration being the signature of a dissipation of energy.

These searches started at the beginning of the twentieth century (De Sitter, 1928) even though the observations then had too poor an astrometric accuracy and did not extend over a sufficiently long period of time. Table 17 gives the values of acceleration obtained for the first three Galilean satellites. The first results were wrong because of the deceleration of the Earth's rotation, so the solar time scale used at that time was not uniform. The apparent acceleration of the satellites was in fact the deceleration of the Earth's rotation! However, after taking this effect into account, a real acceleration was found, but due this time to forgotten long-periodic terms in the motion of the satellites, mistaken for a possible secular acceleration.

It was necessary to wait until the beginning of the 2000s and the use of numerical models to reach an internal precision of the models at the level of the physical effects we were looking for. In particular, in spite of the efforts made at the end of the twentieth century, the accuracy of the equations (internal precision) was still of the order of several hundred kilometers over one century, i.e. of the same order of magnitude (or even a little more) than the effects of the tides themselves. In the same way, the satellites were still modelled as points, which added a little more to the overall error of the model. The new models now take into account not only the usual N-body perturbations and Jupiter's oblateness but also its extended gravitational field (harmonics c_{20} and c_{22}), the precession of Jupiter, and the effects of tides in Jupiter and in Io (cf. the Section on inequalities).

After improving the dynamical model by taking into account all the long period terms, it was possible to detect the true acceleration of the satellites. The last line in Table 17 provides updated values for this acceleration, which are in agreement with the measured flux of heat at the surface of Io (Lainey et al., 2009). The acceleration is then explained as tidal effects of Jupiter on Io, dissipating energy inside the satellite.

Table 17: Acceleration found for Io, Europa and Ganymede.

10^{-11}/year unit	n'_1/n_1	n'_2/n_2	n'_3/n_3
De Sitter (1928)	+33 (±5)	+27 (±7)	–15 (±6)
Greenberg (1986)	+32 (±8)	–16 (±4.5)	–16 (±4.5)
Goldstein (1996)	+70 (±75)	+56 (±57)	+28 (±20)
Vasundhara et al. (1996)	+22.7 (±7.9)	–6.1 (±9.3)	+10.6 (±10.6)
Aksnes et al. (2001)	+54.7 (±16.9)	+27.4 (±8.4)	–27.4 (±8.4)
Lainey et al. (2009)	+4.0 (±11.0)	–5.0 (±7.0)	–7.0 (±7.0)

4 CONCLUSION: PROGRESS ON THE ASTROMETRIC ACCURACY OF THE OBSERVATIONS

Since 1610 the Galilean satellites have been regularly observed: astrometric observations were made during these four centuries and the dynamical models took advantage of this long series of observations. Coherence between the accuracy of the dynamical models and the observations was necessary. Improvements in both the models and the observations have allowed us to determine today some parameters that were not accessible several decades ago. The goal of astrometry has always been to reach another digit in the accuracy of the measurement. Each time a new digit is obtained, our knowledge of the Jovian system increases from several thousands of kilometres of accuracy 400 years ago to a few kilometres today. We may see future progress coming soon: the analysis of old observations will allow us to reduce past observations with today's accuracy using new star catalogues such as GAIA (e.g. see Arlot et al., 2018).

Finally, it is our hope that a permanent space probe will orbit in the Jovian system. Then, the astrometric accuracy will reach a few meters and will offer us a better understanding of those wonderful worlds that are the Galilean satellites.

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Dr Jean-Eudes Arlot was born in France in 1948 and became an astronomer in astrometry and celestial mechanics. He first worked at the U.S. Naval Observatory in 1974 while observing the Galilean satellites with Dan Pascu in order to prepare the navigation of the Voyager mission. He joined the French CNRS and developed a new astrometry of the natural planetary satellites and analyzed and used old observations in his thesis, which he defended in 1982. He published a dynamical model and ephemerides of the Galilean satellites, predicted mutual events of these bodies, and organized worldwide campaigns of observations. He became Director of the Institut de Mécanique Celeste et de Calcul des Éphémérides from 1992 to 2001. He was Chairman of the IAU Working Group on Natural Planetary Satellites and Vice-President of the Ephemerides Commission. He provided lessons in astrometry for students at Paris Observatory and supervised eight Ph.D. theses on astrometry and celestial mechanics. He made many astrometric and photometric observations of Solar System objects. IAU minor planet 17893 discovered in 1999, was named after him. He promoted the building and the use of a sub-micrometric digitizing device for photographic plates and proposed a new use of these data. He is working on the history of the ephemerides and arranged the digitizing of the complete collection of *Connaissance des temps*, the ephemerides published since 1679. He published and coordinated several books such as *The 2004 Transit of Venus* and *Astronomie au Service de Tous*. He has prepared encyclopedia articles, and an “Introduction to Ephemerides”. He is now Astronomer Emeritus at Paris Observatory.