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ANALYSIS OF FRENCH JESUIT OBSERVATIONS OF IO MADE IN CHINA IN AD 1689–1690

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Abstract: The methods and quality of seventeenth century timings of immersions and emersions of the Galilean satellite Io were studied. It was found that the quality of the observations was very good but that in the cases where these observations were used for longitude determinations, the results were impaired by the inaccuracy of Cassini's ephemerides that were used.

Keywords: geographical longitude, China, clock correction, Io immersion, Io emersion

1 INTRODUCTION

The rise of the colonial powers in Western Europe during the seventeenth century fuelled by travels to distant countries created a need for methods to determine geographical longitude. The methods available at the end of the seventeenth century involved timings of astronomical events that were simultaneous for all observers on the Earth, such as lunar eclipses or immersions and emersions of the satellites of Jupiter. Timing such an event at the local time in two different locations and calculating the time difference between the timings determined the longitude difference between the two locations. These timings required a precise knowledge, preferably accurate to one second, of the local times. In the seventeenth century, timings were in general made with pendulum clocks that, however, were not very reliable. During his voyage to Siam the French Jesuit missionary-astronomer Guy Tachard (1648–1712; Orchiston et al., 2016: 31–32) found that his master clock was slow by more than three minutes per day (Tachard, 1686: 332). Consequently, these clocks had to be rectified frequently by determining the apparent (true) local solar time from some external source. Also needed were accurate tables of times of lunar eclipses or tables for calculating immersions and emersions of the Galilean satellites, such as those issued by the Paris Observatory Director, Giovanni Domenico Cassini (1625–1712) in 1683. Immersions and emersions of the Galilean satellites were the preferred events to use for determining the longitude because these events occur frequently and could be used practically every day. Lunar eclipses are not very frequent and the shadow edge is not well defined, which makes accurate timings difficult. Cassini (Goüye, 1688: 232) wrote an extensive article on how to use observations of the Galilean satellites in order to determine the longitude.

Jean de Fontaney (1643–1710), a French Jesuit, was asked by King Louis XIV to set up a mission to China in order to spread French and Catholic influence at the Chinese court. Father Fontaney assembled a group of five other Jesuits to accompany him, all highly skilled in sciences: Joachim Bouvet (1656–1730), Jean-François Gerbillon (1654–1707), Louis Le Comte (1655–1728), Guy Tachard (1651–1712), and Claude de Visdelou (1656–1737). Before setting out for the Far East, they were admitted to the Royal French Academy of Sciences and were trained and commissioned to carry out astronomical observations in order to determine the geographical positions of the various places they would visit, and to collect various types of scientific data (see Udias, 1994; 2003).

After being provided with all the necessary scientific instruments, the Jesuit Fathers sailed from Brest on 3 March 1685 with Father Fontaney as leader. After spending some time in Siam,[1] where Tachard remained (see Orchiston et al., 2016), they finally arrived in Peking on 7 February 1688. The Jesuits were well received by the Kangxi Emperor (Figure 1). Father Bouvet and Father Gerbillon stayed in Peking, teaching the Emperor mathematics and astronomy.

Françoise Noël (1651–1729) was sent in 1684 as a missionary for Japan and arrived in Macao in August 1685. After trying in vain to reach Japan, he was sent to China where he besides making astronomical observations also translated the works of Confucius. He returned to Europe in 1709 and published his work *Sinensis imperii libri classici sex* in Prague in 1711. A detailed account of the mission can be found in the excellent paper by Landry-Derons (2001).

Jean de Fontaney returned to Europe in 1699 but went back to China in 1701, then returned to France in 1702 where he became Rector of the Collège Royal Henry-Le-Grand. Joachim Bouvet later served as the Chinese Emperor's envoy to France and returned to his home country in 1697. In 1699 he arrived in China for the second time and from 1708 to 1715, he was engaged in a survey of the country and the preparation of maps of its various provinces. Jean-François Gerbillon remained in China working for the Chinese Emperor among other things as interpreter for a treaty with Russia regarding the

boundaries of the two empires. Louis Le Comte returned to France in 1691 as Procurator of the Jesuits. In 1697 he published *Nouveaux Mémoires sur l'État Présent de la Chine*. Claude de Visdelou acquired a wide knowledge of the Chinese language and literature. In 1709 he moved to Pondicherry in India where he remained until his death.

2 ADJUSTING A CLOCK FOR TRUE LOCAL SOLAR TIME, THE 17TH CENTURY WAY

Two main methods were used to rectify the clocks: using the altitude of a reference star and using two identical altitudes of the Sun, before and after noon. These will be investigated below.

2.1 Using a Reference Star

This method had the advantage that it could be used almost at any time of the day or night and thus in rather close connection with the timing observation. In most cases a star was used as a reference; since stars are point-like objects, well-defined location and altitude measurements only had to be corrected for atmospheric refraction. If the Sun was used, one of the solar limbs had to be used to get a well-defined altitude and you then also had to correct for the semi-diameter of the Sun as well as for refraction.

Given quantities:

a = the known altitude of a reference star, measured and corrected for refraction.
δ = the known declination of the star from a star catalogue.
α = the known right ascension of the star from a star catalogue.
Both the declination and right ascension of stars are slowly varying quantities with time and a reasonably up-to-date star catalogue had to be used.
α_S = the known right ascension of the Sun, computed for the given date or taken from a pre-computed table.
ϕ = the known geographical latitude of the location, measured earlier.
H_0 = the measured local clock time of the observation. Time is reckoned from noon and negative before noon.

We then have the following relation (after Meeus, 1998):

$$\sin a = \sin \phi \sin \delta + \cos \phi \cos \delta \cos H \qquad (1)$$

We use (1) to compute the hour angle H. We choose the positive value of H if the reference star is west of the meridian and otherwise the negative value. The sidereal time, θ, is then $\theta = \pm H + \alpha$. The hour angle of the true Sun is $H_S = \theta - \alpha_S = \pm H + \alpha - \alpha_S$. This is the apparent local solar time. Comparing this with the measured clock time will give the clock cor-

rection $\Delta = H_S - H_0$. In case the Sun itself was used as the reference star, $H_S = \pm H$.

As an example where the Sun's altitude was used, we can use one of the observations made by Father Noël to determine the longitude of Hoai-ngan (Huai'an) in China on 14 September 1689 (*Mémoires*, 1729: 779). The geographical latitude was 33° 34′ 40″. The clock time was 1 hour 50 minutes after noon and the corrected altitude of the Sun was then 52° 47′ 4″. The declination of the Sun was 3° 11′ north. Using the formula above we compute the true local solar time as 1 hour 31 minutes 58 seconds, thus the clock was 18 minutes 2 seconds fast.

Figure 1: The Kangxi Emperor (en.wikipedia.org).

The same observation also timed and measured the altitude of the stars α Lyrae (Vega) and α Aquilae (Altair) just before the emersion. The computation in this case gives a clock correction of 20 minutes and 19 minutes 45 seconds respectively. Unfortunately, Father Noël identified what was the satellite Ganymede wrongly as Io in this observation.

The right ascension of the Sun is a function of time, changing by about 1 degree per day. In order to determine the current value using tables of the solar right ascension set up for instance for Paris you needed to have some previous idea of what the longitude difference to Paris of

your location was, or use successive approximations in order to find the current solar right ascension for your local time.

2.2 Using Two Altitudes of the Sun

The fundamental idea is to measure the clock times when the Sun has the same altitude before and after noon. The clock noon will be the average of these times. Often the upper limb of the Sun was used. However, the afternoon timing has to be corrected for the change of the Sun's declination between the measurements and the altitudes corrected for atmospheric refraction. Sometimes the upper limb was used before noon and the lower limb was used after noon. Then you will then also have to correct for the semi-diameter of the Sun. The drawback with this method was that the computations were quite involved and that the measurements had to be made during daytime while the lunar eclipse or immersion/emersion observations were normally made after sunset and thus there could be a rather long time interval between the determination of the clock correction and the application of it during which the clock correction could have changed.

2.2.1 Father Fontaney's Method

Jean de Fontaney has described this method in detail (*Mémoires*, 1729: 860) and applied it to several observations. Following is my English translation:

> Of all the methods that one uses to correct the clock by observations of the Sun, observed before and after noon, I have chosen the following as I am more used to it than to other methods.
>
> I take the difference between the times of observation in the morning and in the afternoon. I change the half of this difference to degrees of the parts of the great circle that gives me how much the Sun, at the morning observation, is distant from the meridian, more or less precisely. With this distance [*H*], the complement of the altitude of the pole [ϕ] and the corrected altitude [*a*] of the upper limb of the Sun, I find what is called the solar angle [ξ], by this analogy: *As the sine of the complement of the corrected altitude of the Sun is to the sine of the complement of the altitude of the pole; so is the sine of the distance of the Sun from the meridian (the hour angle) to the solar angle.*
>
> I then take the difference of the declination of the Sun in 24 hours on the day of observation of which I take the part of the difference in declination proportional to the interval of observation before and after noon, to which, as the Sun describes a parallel with the equator, I add (i.e. divide by cos δ) the proportion coming from the difference between the equator and the parallel of the day: and with this difference of declination increased in this way I

have: *As the sine of the solar angle is to the part of the difference in declination, proportional to the interval between the observations, increased by the proportion of the equation to the parallel of the day: so is the sine of the complement of the solar angle to parts of 360˚ hour angle, which, reduced to time measure, gives the correction to the time of observation in the afternoon.*

> This correction, when the Sun is in the descendant signs, has to be added to the hours in the afternoon and to be subtracted when the Sun is in the ascendant signs.

> With the time in the afternoon, thus corrected, I take the difference between the times in the morning and the corrected afternoon time, I add half of this difference to the morning observed time; the sum gives the hour that the clock shows when the Sun at true noon, and the difference between the time that the clock shows and 12 hours, is how much it is slow or fast. The demonstration of this practice is very easy unless you think the movement of the Sun would be pointless to take into account.

This method was also used by Tachard (1686: 76, 78) when he determined the longitude of Cape Town in 1685, using the upper and lower limbs of the Sun.

2.2.2 Mathematical Formulation

Expressed in mathematical language the first statement is equivalent to

$$\sin \xi = \sin H \cos \phi / \cos a \qquad (2)$$

where ξ is the 'solar angle',[2] *H* the hour angle of the Sun, ϕ the geographical latitude, and *a* the altitude of the Sun, corrected for refraction.

The second statement can be written

$$\Delta H = -(\Delta\delta / \cos \delta) / \tan \xi \qquad (3)$$

where ΔH is the time correction due to the change in declination, δ is the solar declination, and $\Delta\delta$ the change in solar declination between the morning and afternoon measurement.

Both of these formulae can be verified using standard spherical trigonometry. If T_1 is the time of the altitude measurement before noon and T_2 the time of the corresponding measurement after noon, the formula for the clock correction in hours is $\Delta = T_1 + (T_2 + \Delta H - T_1) / 2$.

An example of this method is the determination of the longitude of Si-ngan-fu (Xi'an) on 12 July 1689 by Father Fontaney (*Mémoires*, 1729: 860). He used three pairs of observations of the solar upper limb in the morning and afternoon to set his clock. I have checked his calculations, and they are correct to the seconds within rounding errors.

3 THE OBSERVATIONS

In my analysis I have used observations of immersions and emersions of the Jupiter satellite

Table 1: Observations from Hoai-ngan.

Date	Type	Observation Time			IMCCE Apparent Time (Greenwich)			Longitude	
		h	m	s	h	m	s	°	'
1689-10-07	Emersion	23	13	58	15	16	03	119	29
1689-11-01	Emersion	18	01	20	10	03	07	119	33
1689-11-08	Emersion	19	56	14	11	58	11	119	31
1689-11-15	Emersion	21	50	30	13	52	34	119	29
1689-12-01	Emersion	20	05	00	12	07	33	119	22
1690-09-10	Immersion	22	12	20	14	18	29	118	28
1690-09-17	Immersion	24	12	23	16	15	28	119	14
1690-10-05	Emersion	19	16	08	11	16	43	119	51
1690-10-12	Emersion	21	13	00	13	13	19	119	55
1690-10-19	Emersion	23	08	50	15	10	02	119	42
1690-12-04	Emersion	23	30	40	15	31	48	119	43
							Average	119	29

Io in 1689 and 1690 in China taken from Pingré (1901), supplemented with information taken from *Mémoires* (1729) and Goüye (1692). I have deleted two observations that are certainly other Galilean satellites mistaken for Io.

It is impossible to determine which of the ephemeris tables issued by Cassini for the movements of the four Galilean satellites were used by the Jesuit observers in China. The tables that I have been able to consult (Cassini, 1668; 1693) do not by my computation render the precise time values cited in the observations.

Another problem is that Cassini's tables are not accurate, having time errors of some minutes: "It is true that often there are still a few minutes difference in time between the Ephemerides and the Observations." (*Mémoires*, 1730: 180; my English translation).

Also, the immersion and emersion times computed from the tables and cited by the Jesuits in the *Memoires* are only given to one minute precision (or in one case, to half a minute precision). As I have been mainly interested in the quality of the Jesuit observations, I decided to use as a benchmark a modern ephemeris program, available on the web at the Institute de Méchanique Celeste de Calcul des Éphémérides (IMCCE), in order to determine the immersion and emersion times.

An immersion or emersion of a satellite is not an instant in time; for Io, the event typically has a duration of a little more than four minutes. A time interval of four minutes corresponds to about 1° of longitude, thus it is important to define the precise moments that are chosen to represent the immersion or emersion respectively. For an immersion, the modern definition is the time when the satellite just disappears completely in the shadow of Jupiter, the 'last speck', and for an emersion, it is the first appearance, the 'first speck'. These are given in the IMCCE ephemeris in Universal Time (UT), with a precision of seconds. In practice, for an observer the precise timing would to some extent depend on the telescope's magnification. With a stronger magnification, one would expect to follow a dimin-

ishing satellite crescent a little longer and discover its appearance a little earlier. It is then to be expected that the observed timing of an immersion would be slightly too early and for an emersion slightly too late as compared with the ephemeris, resulting in a slightly-too-large longitude difference for emersions and slightly-too-small longitude difference for immersions. It could also be expected that such timings would be somewhat observer dependent, although the Jesuit missionary-astronomers were trained scientists.

There are six sets of observations for different Chinese locations, and these are discussed separately below. The modern Chinese names are given in brackets.

In the following tables, the times given by the observers are reckoned from noon and are shown in the first column. I have added 12 hours to these times in order to have the standard modern astronomical reckoning from midnight. The observers also use apparent local solar time as was standard during the seventeenth century and used the terminology 'true time' for this. The second column shows immersion/emersion times according to IMCCE where I have converted the UT ephemeris time into apparent solar time using the equation of time as computed from the algorithm in Meeus (1998). The last column shows the longitude computed using the difference in time between the observed immersion/emersion time and the IMCCE time and the relation that 15° in longitude difference corresponds to one hour in time.

3.1 Observation Set 1

These observations (see Table 1) were made by Father Noël from Hoai-ngan (Huai'an) in 1689 and 1690.

The official modern longitude of Huai'an is 119° 8′. As expected, the emersion longitudes are larger than the immersion ones. There are few immersion longitudes, a fact that will increase the average longitude as the emersion longitudes will dominate. Pingré notes that the

Table 2: Observations from Si-ngan-fu.

Date	Type	Observation Time			IMCCE Apparent Time (Greenwich)			Longitude	
		h	m	s	h	m	s	°	'
1689-06-03	Immersion	28	18	00	21	04	16	108	26
1689-06-19	Immersion	26	31	22	19	18	18	108	16
1689-07-12	Immersion	26	36	56	19	23	06	108	28
1689-08-04	Immersion	26	46	56	19	33	24	108	23
1689-10-23	Emersion	20	55	05	13	38	22	109	11
1689-11-08	Emersion	19	15	20	11	58	11	109	17
1689-11-15	Emersion	21	09	07	13	52	34	109	08
							Average	108	44

Table 3: Observations from Canton.

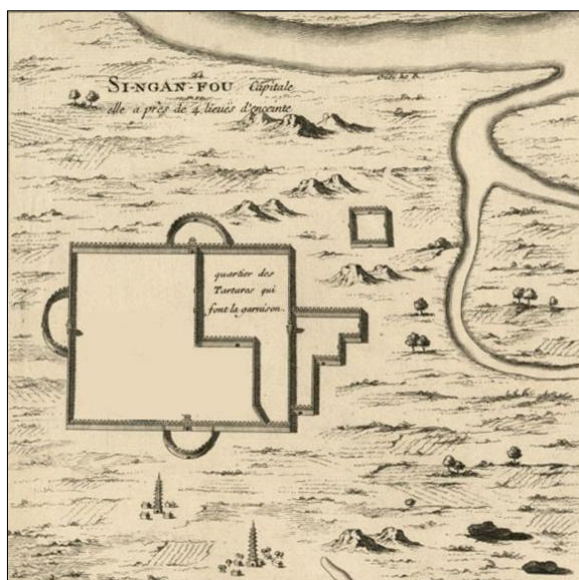| Date	Type	Observation Time			IMCCE Apparent Time (Greenwich)			Longitude	
		h	m	s	h	m	s	°	'
1690-09-10	Immersion	21	49	03	14	18	27	112	39
1690-09-17	Immersion	23	46	14	16	15	34	112	40
1690-10-12	Emersion	20	46	25	13	13	18	113	17
1690-10-19	Emersion	22	42	49	15	10	02	113	12
1690-10-28	Emersion	19	06	46	11	34	17	113	07
1690-11-04	Emersion	21	02	38	13	29	24	113	19
							Average	113	02

Figure 2: Si-ngan-fu (BnF).

location for the observations were a little to the east of Huai'an. The standard deviation of the emersion longitudes is 11′. Father Noël used the
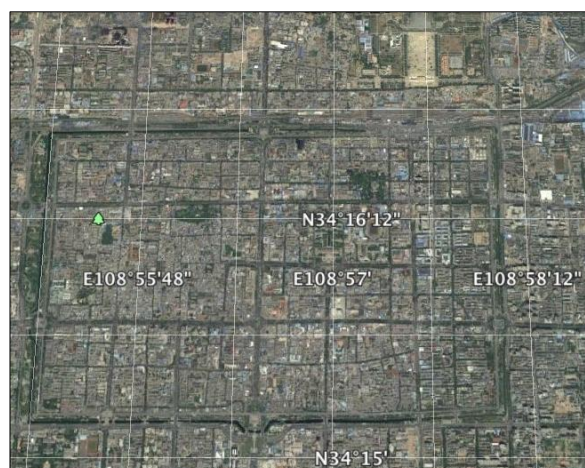

Figure 3: The old city in Xi'an (Google Map Pro).

five first observations (*Mémoires*, 1729: 779) to determine the longitude from Paris as 116° 30′, i.e. 118° 50′ from London. The time errors (all positive) from the cited Cassini ephemerides have an average of 2.6 minutes.

3.2 Observation Set 2

These observations (Table 2) were made by Father Fontaney from Si-ngan-fu (Xi'an) in 1689. Figure 2 shows a contemporary map of Si-ngan-du, while Figure 3 shows the still existing old city layout in Xi'an.

The official modern longitude of Xi'an is 108° 54′. The standard deviations of the immersion and emersion groups are both 5′. Father Fontaney used observations number 3, 5, and 7 (*Mémoires*, 1729: 855) for his longitude determination and got an average of 108° 44′, identical to the average result in the table. This is a pure coincidence, as the cited Cassini ephemerides are in error by about –1.4, 1.8, and 2.1 minutes respectively.

3.3 Observation Set 3

These observations (Table 3) were made by Father Fontaney from Canton (Guangzhou) in 1690.

The official modern longitude of Guangzhou is 113° 16′. The spread is very small within the immersion and emersion groups separately, indicating that Fontanay was a very good observer. The emersion longitudes have a standard deviation of 5′. Father Fontaney used the first and third observations each with three clock corrections where he used his method with pairs of equal solar altitudes. He arrived at the same longitude value as the average in the table (*Mémoires*, 1729: 870). Again this is sheer luck although in this case the errors in Cassini's ephemerides are –0.8 and 0.35 minutes respectively.

Table 4: Observations from Shanghai.

Date	Type	Observation Time			IMCCE Apparent Time (Greenwich)			Longitude	
		h	m	s	h	m	s	°	'
1689-07-28	Immersion	25	42	49	17	38	48	121	00
1689-08-06	Immersion	22	06	24	14	02	11	121	03
1689-08-31	Emersion	19	07	12	11	01	05	121	32
1689-09-07	Emersion	21	04	07	12	57	51	121	34
						Average		121	17

Table 5: Observations from Nankin.

Date	Type	Observation Time			IMCCE Apparent Time (Greenwich)			Longitude	
		h	m	s	h	m	s	°	'
1689-10-16	Emersion	19	37	27	11	42	04	118	51
1689-10-23	Emersion	21	33	50	13	38	22	118	52
1689-11-01	Emersion	17	59	12	10	03	07	119	01
1689-11-08	Emersion	19	54	00	11	58	08	118	58
1689-11-15	Emersion	21	48	13	13	52	29	118	56
1689-12-01	Emersion	20	03	06	12	07	34	118	53
						Average		118	55

Table 6: Observations from Peking.

Date	Type	Observation Time			IMCCE Apparent Time (Greenwich)			Longitude	
		h	m	s	h	m	s	°	'
1690-09-10	Immersion	22	03	29	14	18	29	116	15
1690-10-12	Emersion	21	00	00	13	13	19	116	40
1690-10-19	Emersion	22	56	15	15	09	29	116	41
1690-10-26	Emersion	24	51	14	17	05	25	116	27
1690-11-04	Emersion	21	16	42	13	29	24	116	49
1690-12-13	Emersion	19	39	24	11	52	01	116	51
						Average		116	37

3.4 Observation Set 4

These observations (Table 4) were made by Father Fontaney from Chang-hai (Shanghai) in 1689.

The official modern longitude of Shanghai is 121° 30′. Again, Jean de Fontenay's emersion longitudes are larger than the immersion ones. The spread is extremely small for both the immersion and emersion longitudes: 2′–3′.

3.5 Observation Set 5

These observations (Table 5) were made by Father Fontaney from Nankin (Nanjing) in 1689.

The official modern longitude of Nanjing is 118° 46′. The longitudes are very consistent, with a small standard deviation of 4′. Also here Pingré notes that Fontaney was located to the east of Nanjing.

3.6 Observation Set 6

These observations (Table 6) were made by Fathers Bouvet and Gerbillon from Peking (Beijing) in 1690.

The official modern longitude of Beijing is 116° 23′. The standard deviation of the emersion longitudes is 9′.

4 CONCLUDING REMARKS

From the data we can conclude that the longitudes derived from the emersions are in general a little too large and that those derived

from the immersions are a little too small. This is to be expected, as explained above. Father Fontaney's observations clearly show that he must have been a very skilled observer, given the very good internal consistency in his timings of the immersions and emersions.

In general, all the observations are quite consistent and of good quality, the standard deviations are with one exception very small and the computed average longitudes above agree quite well with the actual longitudes. Looking at the whole data set, the Jesuit fathers had a timing difference of about 20 seconds relative to the IMCCE first and last speck times. Due to the time errors in Cassini's ephemerides that were of the order of two minutes, the contemporary longitude determinations had an inherent error of at least half a degree. Actually, this is not bad, as the Longitude Act, issued on 8 July 1715 by Queen Anne of England, stipulated a prize of £20,000 for a method to determinate longitude to an accuracy of half a degree of a great circle. However, the Jesuit observations were made on firm ground with rather large instruments that had been extensively calibrated. On the heaving deck of a ship you could not expect very accurate results using their methods.

5 NOTES

1. While temporarily in Siam they observed a total lunar eclipse on 11 December 1685 (see Gislén, 2004; Orchiston et al., 2016).

2. When we consider a spherical triangle P is the North Pole, Z the zenith and S the Sun, the angle PSZ is the 'solar angle'.

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