ANALYSIS OF 35 YEARS OF TRANSIT OBSERVATIONS BY LA HIRE AT PARIS OBSERVATORY

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Abstract. Just after the achievement of the construction of the Paris Observatory in 1672, astronomers such as Jean Picard, Jean-Dominique Cassini, and Philippe de La Hire, were deeply involved in observations of the Sun, the Moon, the planets, and the stars. In particular, La Hire used a meridian circle to pursue these kinds of observations in a quasi-daily basis for more than 35 years, from 1683 to 1718; thus leading to very precious and huge registers carefully conserved in the archives of Paris Observatory. In this paper, we make a quantitative and qualitative analysis of this invaluable testimony. In particular, we explain how these observations, dating back to over three centuries ago, could be exploited for constraining modern determinations of basic astrometric parameters.

Key words: Astronomy, History of the Astronomy .

1. INTRODUCTION

Philippe de La Hire (1640–1718) is one of the prominent astronomers of the second part of the 17th and of the beginning of the 18th century. His work goes far beyond astronomy with various and rich works dealing with mathematics, architecture, physics, biology.

Member of the French Academy of Sciences, at the age of 30, he was particularly famous thanks to his *Tables Astronomiques*, for which the first version was published in 1687. These astrometric tables were used as a fundamental reference across the world by many of his contemporary scientists and scholars wishing to know as precisely as possible the positions of the stars, the Moon, and the Sun.

The great advantage of La Hire's observations upon the ones of his predecessors lies in the use of a specific and accurate instrument, that is the meridian circle firmly cramped vertically to the east wall of the Observatory, close to the uncovered oriental tower. Three months were required for La Hire in 1683 to orientate in a

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suitable way and with an optimal precision the instrument in the meridian plane. The use of such device was previously suggested by Picard and Røemer but their projects were systematically dismissed. Note that in England, Flamsteed decided the construction of a similar instrument later in 1689, while La Hire began his observations with this new device in April 1683.

Another significant amelioration of La Hire's observations with respect to previous ones comes from his use of a pendulum clock which enabled him to establish with a one-second accuracy the date of transit of the celestial bodies. Here and in the following of this paper, the word "transit" of a celestial object means the meridian transit which occurs when the object is exactly in the meridian plane, which corresponds to its culmination. This clock was compared daily with the sidereal time directly deduced from the successive transits of selected bright stars. In other words, thanks to the perfect lack of motion of the meridian circle, the precise dating of transits of the brightest stars led to a very accurate determination of the diurnal drift of the mechanical clock. This proved to be a key improvement with respect to previous methods which consisted in monitoring every day the timing at various heights of some specific bright stars. In the following we discuss the contents of the registers held by La Hire during 35 years of regular observations carried out with his meridian circle (La Hire,1683–1718).

2. METEOROLOGICAL DATA AS A BY-PRODUCT OF 35 YEARS OF DAILY OBSERVATIONS

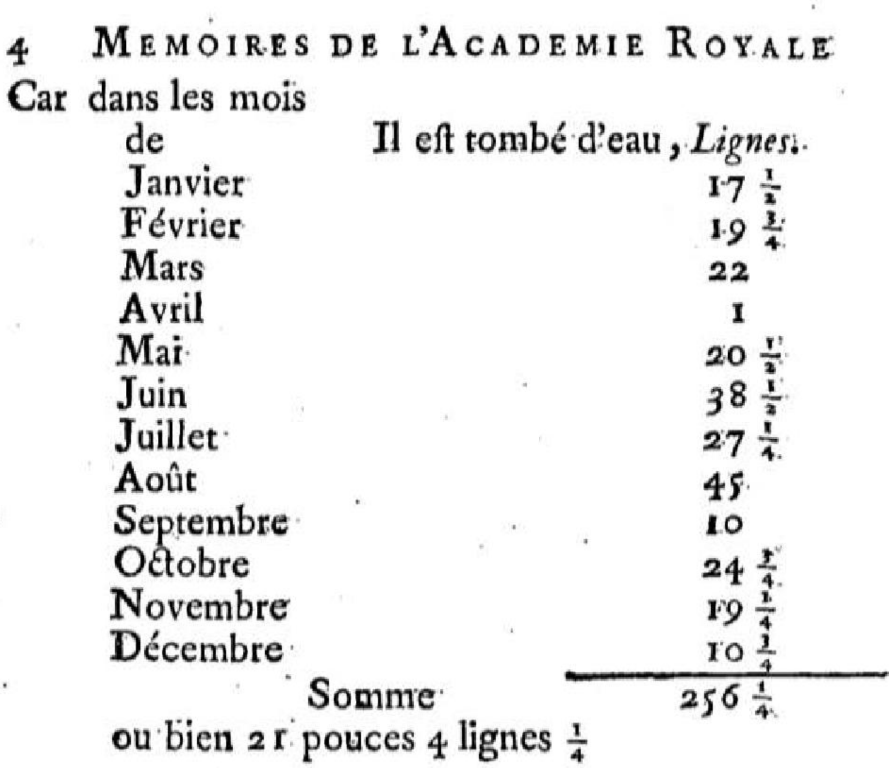
In addition to carrying out astronomical observations, La Hire recorded precious meteorological data. As a result, he published several general reports on barometer, thermometer and rain fall measurements in the yearly publication of the *Mémoires de l'Académie Royale des Sciences*, later quoted as *MARS*. This could be of valuable interest to modern experts in meteorology who want to study the long-term evolution of the daily weather in Paris more than three centuries ago. For example, La Hire made a monthly account of the amount of rainfall at the Paris Observatory during the year 1701, he published his results in *MARS* in 1702 . He noted in particular that despite a period of intensive dryness during spring, with no rain at all in April, the year 1701 was characterised by an abnormal excess of rainfall when summing up all the monthly amounts, as illustrated in Figure 1.

Another precious data concerns the systematic observations of the transit of the Sun, which are described in detail in Section 4. Obviously, whenever this transit observation was possible, this signifies generally (but not systematically) that the weather was rather good at least around noon on the given day. It is, therefore, possible to make a rather complete statistics on the subject. Figure 2 shows the number of transit observations of the Sun reported by La Hire for each year considered. We observe that this number is generally considerably larger after 1700 than before, with a value exceeding generally 200 observations in the first case, whereas it is generally smaller in the second one. La Hire recorded the maximum number of transit events in 1715, three years before he passed away.

In Figure 3, we show on a monthly basis the total number of sunny middays during the 35 years of daily observation ranging from January 1683 to mid-1718. We observe that August is the leading month with 710 transits of the Sun, which corresponds to a mean value of 20 days for the interval of time considered, followed by July with 697 transits. The numbers for the winter months are rather low. We assume that lower temperatures sometimes made astronomers skip transit observations, even if explicit information confirms it in the registers. Figure 4 shows the minimum and maximum values of the number of transit observations during the 35 years. Note that for July, the maximum corresponding to 31 days happened in the year 1701 is 31 days, meaning that the Sun was observable every midday, which is remarkable. Even here, the observations in summer are leading the statistics. At last, we show in Figure 5 the distribution of observations on a monthly basis for the year 1715, which is the leading one with 234 transits in total. This corresponds to a 64 % ratio with respect to one year of 365 days.

3. THE MECHANICAL CLOCK AND ITS CALIBRATION

Very little information is given about the mechanical clock used for the timing of transits by La Hire. Along the comments found in his notebooks, some explicit words make reference to both a new and an old clock which are sometimes linked to one another by a bias at a given date. During the first years of observations, from 1683 to 1687, the astronomer noted scrupulously the time of transit of the brightest stars, as Sirius, Aldebaran, Arcturus, Rigel, Vega, etc. If the mechanical clock were perfectly stable, the difference of time transit of any given star from one night to the following one, expressed in mean solar time, would be - 3mn. 56sec., because the length of a sidereal day is exactly 23h 56mn 04sec. Therefore, by using the successive time of bright star transits at one or a few nights interval, it is possible to extrapolate from the difference O-C (Observed - Calculated) the drift of the mechanical clock involved. Figure 6 shows an example of La Hire's notes about such an extrapolation. He notifies that by referring to the transit of the star β Aquarius, the clock was slowing down by an 20" over a 13 day interval, which from a direct interpolation corresponds to a drift of 1.5"/day. By applying such a method, we illustrate in Figure 7 the daily drifts of the mechanical clock extrapolated from bright stars' transits for the whole year 1686. We observe that the maxima of the daily drifts do not exceed ± 10 sec. of time, with a maximum value around + 8 sec. (acceleration) and a minimum one of - 4 sec. (deceleration). Using these daily behaviours, we plot in Figure 8 the cumulative drift undergone by the clock. Note that it reaches



4 MEMOIRES DE L'ACADEMIE ROYALE

Car dans les mois de	Il eſt tombé d'eau, *Lignes.*
Janvier	17 $\frac{1}{2}$
Février	19 $\frac{3}{4}$
Mars	22
Avril	1
Mai	20 $\frac{1}{2}$
Juin	38 $\frac{1}{2}$
Juillet	27 $\frac{1}{4}$
Août	45
Septembre	10
Octobre	24 $\frac{3}{4}$
Novembre	19 $\frac{1}{4}$
Décembre	10 $\frac{1}{4}$
Somme	256 $\frac{1}{4}$

ou bien 21 pouces 4 lignes $\frac{1}{4}$

Fig. 1 – Monthly amounts of rainfall recorded by La Hire at Paris Observatory for the year 1701, published in *MARS* for the year 1702.

1500 sec., that is to say 25 mns. in absolute value.

The slow daily drifts described above should not be confused with another type of correction made by La Hire several times per year. For technical reasons, he had to add or subtract an artificial bias of a few minutes (very often 5 or 10 minutes). We can suppose that the daily drift increases sometimes more or less strongly according to the bias chosen for calibrating the clock. Fortunately, these biases are generally noted by La Hire in his registers. Figure 9 shows such an example of a 10 mns. clock bias correction made operated by La Hire on October 26th,1685.

4. A MAJOR CONTRIBUTION: MEASUREMENTS OF THE SUN'S TRANSITS

By far the most important contribution of La Hire during his 35 years of observations at the meridian circle of Paris observatory concerns the transits of the Sun.

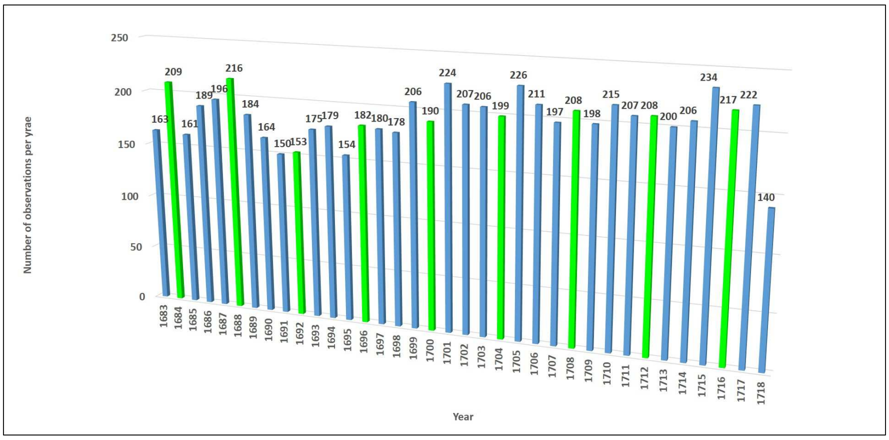


Fig. 2 – Annual number of transits of the Sun recorded by La Hire between 1683 and 1718. The leap years are represented in green, while the others are shown in blue.

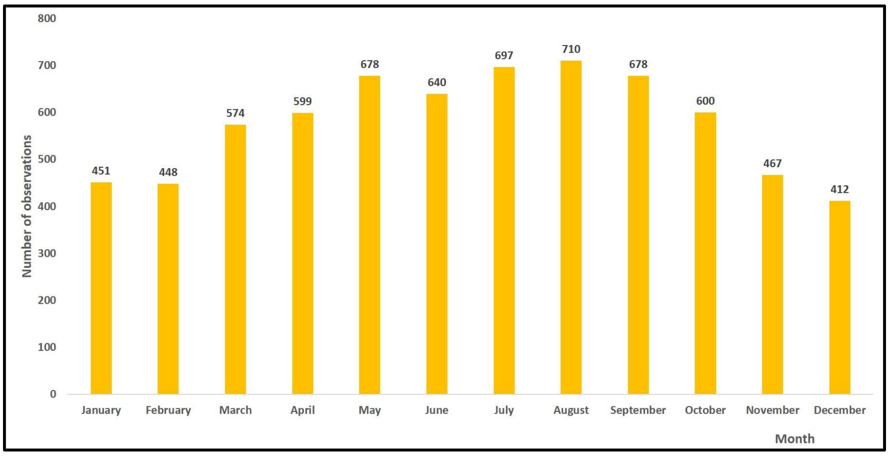


Fig. 3 – Monthly number of transit of the Sun recorded by La Hire between January 1683 and December 1718.

For this purpose, he carefully recorded on a daily basis the precise time of transit of both the western and the eastern edge of our star. He then deduced the transit of the centre by determination of the mid-time interval between these two transits. The transit times are obtained directly from the mechanical clock which is calibrated on a daily basis or every few days with the help of the transits of a set of very bright stars, as this was explained in the previous section. Moreover, La Hire determined the height of the superior edge of the Sun above the horizon during the transit. Note that the four parameters (the three transit times and the height) mentioned above were not systematically recorded in the registers. Very often only two values of transit time are

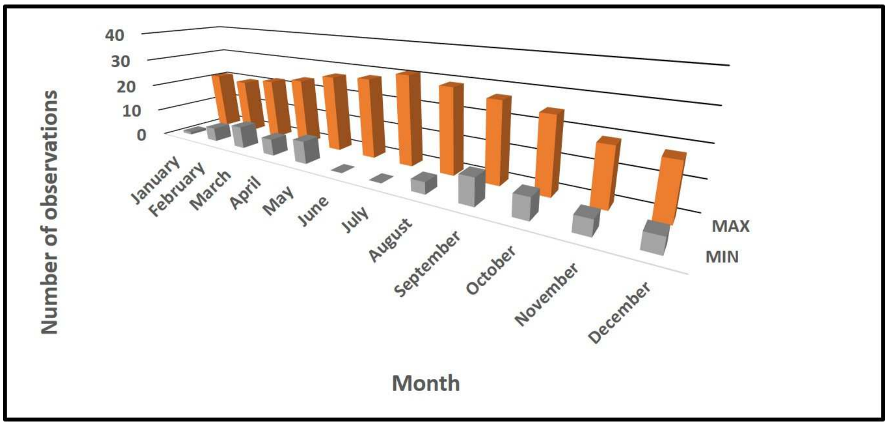


Fig. 4 – Maximum and minimum values of the monthly recorded number of transits of the Sun observed by La Hire between January 1683 and December 1718.

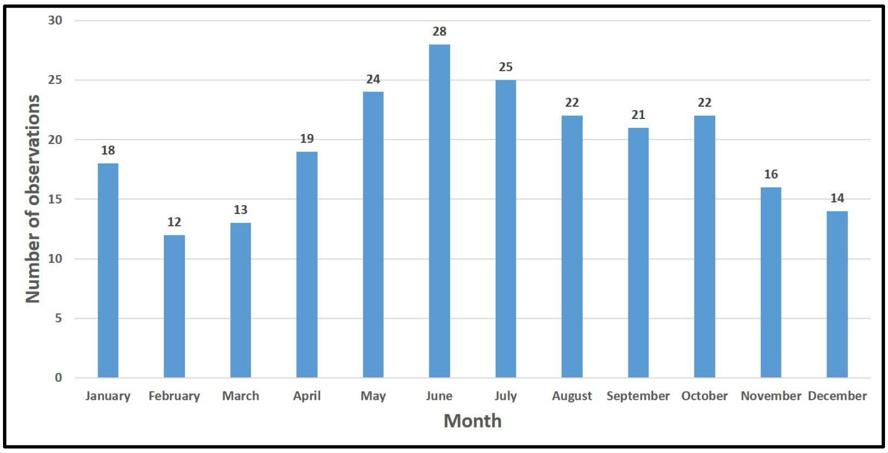


Fig. 5 – Distribution of the number of observations of the transit of the Sun for the year 1715 which is characterised by the maximum value of 234 transit observations.

given instead of the three fundamental ones. In that case the lacking transit time can be extrapolated or interpolated from the two other ones. In addition, numerous measurements of the height at meridian are missing. In Figure 10, we show an example of a solar transit record with the available determination of the four parameters.

In this study, we report on a total number of 6 954 observations of solar transits carried out by Philippe de La Hire, and for which we have constructed the associated database covering the period from January 1683 to April 1718. La Hire's elder son, Gabriel-Philippe de La Hire (1677-1719), continued his father's work for roughly one year with 150 additional transit observations, until he died at his turn.

Polaris ſtellæ altitudo maxima circa $7^h\,8'$

$51^\circ.\,14'.\,55''$

V β Tranſitus ——— $8^h.\,11'.\,11''$

Tardavit horologium pro 13 diebus $20''$.

Fig. 6 – Example of determination of lateness of the mechanic clock starting from transits at 13 days interval of the star β Aquarius. At top, determination of the height of Polaris above the horizon during its transit.

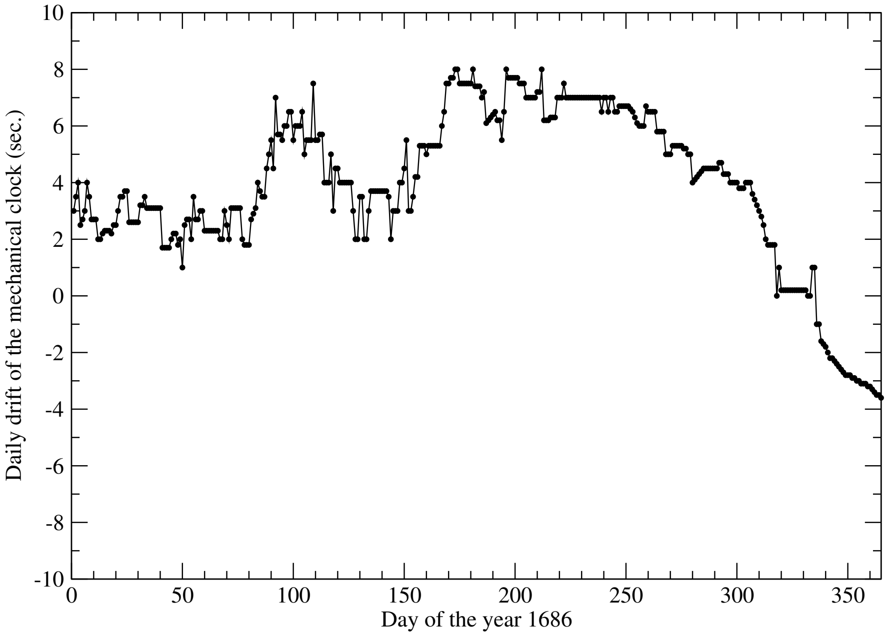


Fig. 7 – Daily drift of the mechanical clock used by La Hire during the year 1686, extrapolated from stars transits

Invaluable information could undeniably be deduced from the data above, it concerns three kinds of measurements: *(i)* the equation of time, *(ii)* the transit duration, and *(iii)* the height of the Sun above the horizon. In the following sub-sections we detail the specificities of each of these measurements.

4.1. THE EQUATION OF TIME

The equation of time which differentiates the true solar time from the mean solar time can be calculated from the drift of the transit time of the solar centre from

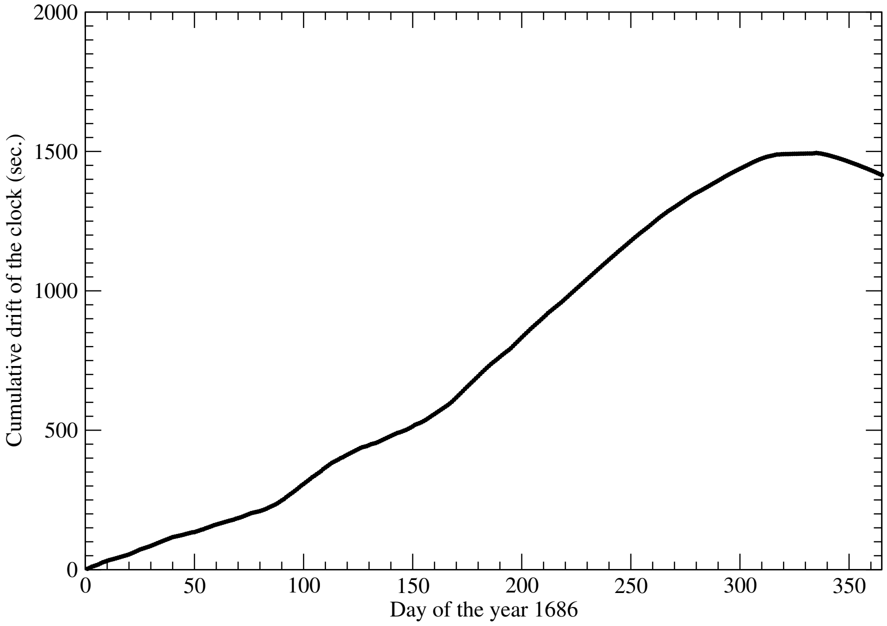


Fig. 8 – Cumulative drift of the mechanical clock used by La Hire during the year 1686, extrapolated from stars' transits.

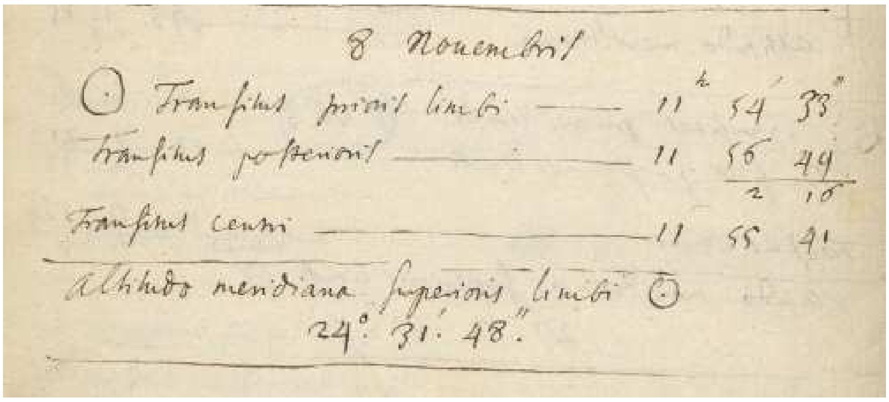
26 Octobre 1685.
promotum horologium 10

Fig. 9 – Example of bias voluntarily introduced by La Hire on his mechanical clock.

one day to the other. Figure 11 shows the equation of time as deduced from La Hire registers in the year 1688. The numerous gaps characterising the curve are due to the artificial biases operated by the astronomer, as mentioned in the previous section. Once these biases have been corrected for Figure 12, we obtain a new continuous curve which resembles a lot the theoretical one, if we except the daily clock drift which increases gradually and should also have to be taken into account for a precise analysis.

4.2. THE DURATION OF SOLAR TRANSIT

The interval of time between the western edge and the eastern edge transits of the Sun, which can be quoted as "the transit duration", and noted as τ in the following depends on three parameters: *(i)* the angular size of the Sun which is directly



8 Nouembris

☉ Transitus prioris limbi —— 11h 54' 33"

transitus posterioris —— 11 56 49

2 16

Transitus centri —— 11 55 41

altitudo meridiana superioris limbi ☉

24°. 31'. 48".

Fig. 10 – Transit of the Sun as described by La Hire in his notebook for the date of November 8th, 1684. The measurements concern the transit of the western edge of the Sun (11h 54' 33"), of the eastern edge (11h 56' 49") and by interpolation the transit of the centre (11h 55' 41"). A fourth element is the height above the horizon of the superior edge of the Sun (24° 31' 48").

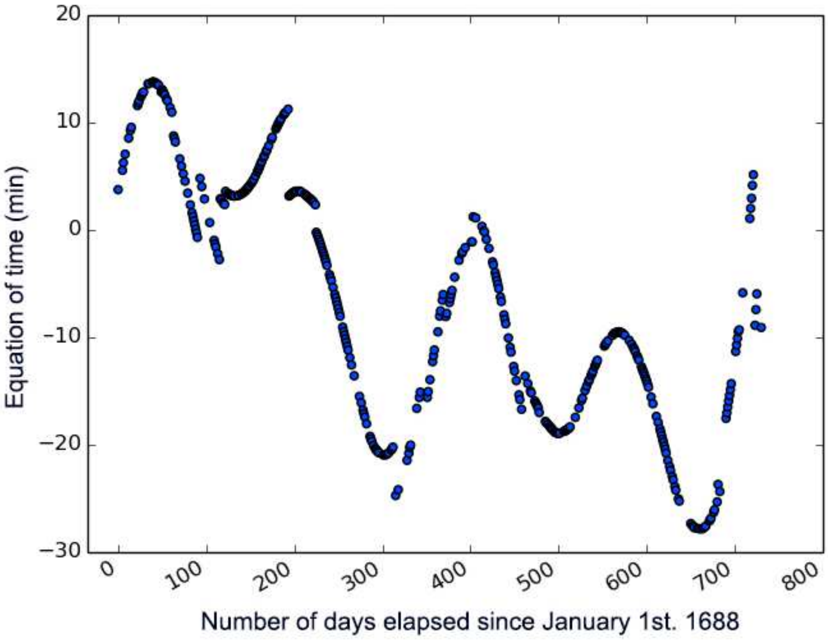


Fig. 11 – Equation of the time established from La Hire's raw data of the time of meridian transits of the Sun for the years 1688 and 1689.

related to the Earth-Sun distance, *(ii)* the relative angular velocity of the Sun which depends on the position of Earth along its orbit with respect to the perihelion, and

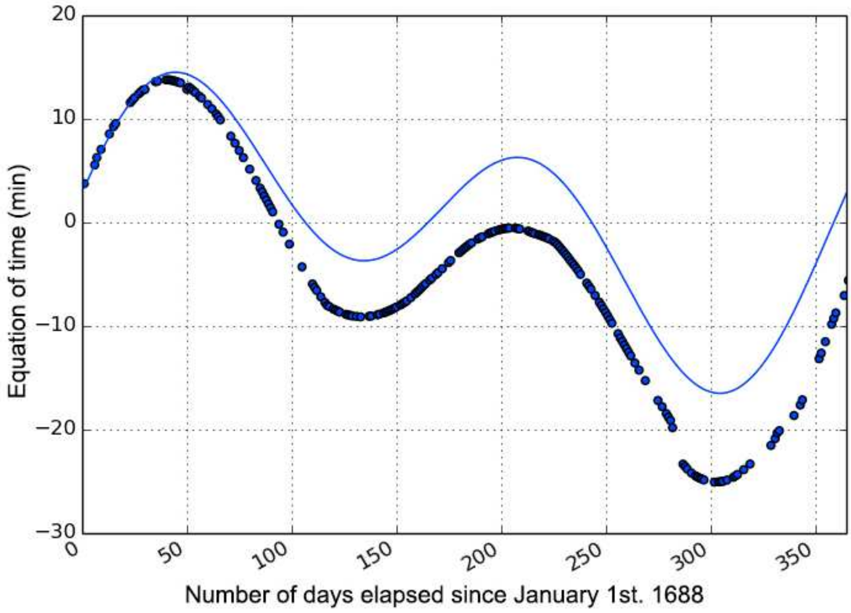


Fig. 12 – Equation of time of the previous figure after correction of the artificial biases.

(iii) the declination of the Sun above or below the celestial equator which affects the difference of hour angle between the two edges. In Figure 13, we show the variation in transit duration over a 2000 days time span starting January 1st, 1683, together with the theoretical curve, obtained from accurate ephemerides of the Sun based on classical celestial mechanics and updated parameters.

Notice that La Hire's transit records were analysed scrupulously by several authors of the 20th century in order to investigate the possible variations of the diameter of the Sun, deduced from the transit duration itself. M. Toulmonde (1995,1997) concentrated a study on the 326 measurements carried out in 1683–1684; he obtained a mean value $\Delta\tau$ = 0.82 sec. between the value deduced from the observations and the theoretical one, with a dispersion σ = 0.64 sec., with 22 measurements larger than 2σ. Moreover, Ribes *et al.* (1987, 1988) took into account the total number of roughly 7000 measurements to calculate mean annual values of the duration of the transit. They obtained the values of 964.58” from 136 values in 1683, 965.75” from 186 values in 1684, with respective dispersions $\sigma = 5.5$” and $\sigma = 5.2$”. As explained in great details by Toulmonde(1997), the measurement of the diameter of the Sun requires several corrections. Some have a physical origin such as the darkening of the solar disk near the edges, the wavelength dependence of the observation, the influence of the atmospheric refraction and turbulence. However, the leading effect on

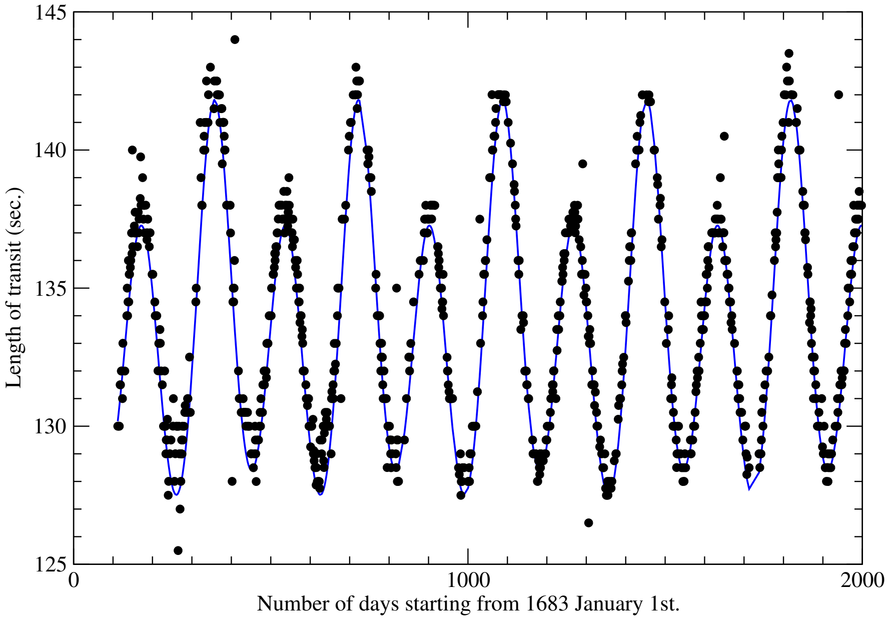


Fig. 13 – Variations of the duration of the transit of the Sun for 2000 days (5.47 y) deduced from La Hire's observations. The curve in blue is a rough theoretical determination

the measurement comes from the optical device, which is accompanied by limiting phenomena as the chromatic aberration, the distortion and the diffraction. For the solar transit observations carried out by La Hire more than three centuries ago with a lens diameter of a few centimeters, the effect of diffraction reaches several arcseconds, which limits considerably the accuracy of the measurement of the diameter. On this topic Toulmonde(1995) explains that this constitutes by far the main cause for the artificial diminution of the determination of the radius of the Sun, which in fact stays at the same value within the error bar of ± 1.5".

4.3. THE HEIGHT OF THE SUN ABOVE THE HORIZON

The height determination of the Sun above the horizon, which was not systematically recorded, was calculated with great care by La Hire. It should be of great interest, for it involves astronomical parameters whose values should be constrained in the scope of a modern analysis. First it depends on the declination of the Sun which varies between the two extrema $\pm\varepsilon = 23°27'$ (which correspond to the solstices). We must notice that the obliquity ε undergoes the nutation, classically quoted as "$\Delta\varepsilon$" which was discovered by James Bradley (1693 – 1762) exactly 30 years after La Hire's death, *i.e.* in 1747–48 (Bradley, 1747). The nutation $\Delta\varepsilon$ is highly dominated by a sinusoidal oscillation with a period of 18.6y and an amplitude of 9". Although this amplitude is rather small and seems at the limit of the accuracy of La Hire's observations, it was naturally lacking in the computations of the astronomer which lead to the establishment of his *Tables Astronomiques* (La Hire, 1687). Second the height of the Sun during a meridian transit depends on the refraction, which heightens the whole disk of the Sun by an angular quantity which depends on the height of the Sun h_S itself. Note that the refraction reaches $30'$ roughly when the Sun is at the horizon level, and decreases strongly with respect to an increasing value of h_S. Nevertheless its value is still 1' at $h_S = 20°$. La Hire established himself his own tables of refraction which can be found in the *Tables Astronomiques* and give the amount of angular correction to be applied as a direct function of height. On this topic he studied the possibility that the values are influenced by the meteorological conditions, particularly the temperature, for which he could not identify a significant effect. Figure 14 shows the variations of the height of the superior edge of the Sun as measured by La Hire for the year 1688. In order to deduce the declination of the Sun from this kind of observation which is related to the centre of the Sun, we must subtract from this value the angular radius of the Sun which is known with great accuracy from our present knowledge. Once this subtraction is performed, it is necessary to take into account the refraction and the nutation, as pointed out above. The fact that such height measurements have been conducted for a 35 year period should lead to accurate determinations of the obliquity ε, as well as of the instant of equinoxes and solstices, whose values shall be confronted with those resulting from modern computations.

5. TOWARDS A CATALOGUE OF STARS

The observations of Solar and stellar transits are of fundamental interest for the construction of a general catalogue of stars, as La Hire himself presented one in his famous *Tables Astronomiques*. Indeed, the comparison of the transit time Δt of two bright stars observed during the same night could lead to the determination of their difference in right ascension $\Delta\alpha$ in a straightforward manner, by the direct relationship: $\Delta\alpha = 366.25/365.25\Delta t$, where the numerical ratio involved in this equation corresponds to the ratio of one mean solar day to one sidereal day. In addition the difference of height Δh of the two stars during their transit, when assuming it is corrected from the value of their respective refraction, is such as : $\Delta\delta$ = Δh, where $\Delta\delta$ stands for the difference of declination. Therefore, by associating the differences $\Delta\alpha$ and $\Delta\delta$ from various pairs of stars it becomes possible to construct a global star catalogue. When transit measurements for the stars happen in the same night, this

Table 1

Number of intra-night inter-comparisons between bright stars during the year 1686. The last column to the right shows for each star the total recorded number of intra-night inter-comparisons between the bright stars for this year. The acronyms are as follows: SI: Sirius; AD: Aldebaran; RI: Rigel; SP: Spica; Pr.: δ Orionis; Se.: ϵ Orionis; Te: ζ Orionis; AR: Arcturus; PR: Procyon; AA: α Aries; RE: Regulus; OC: Ω Cernicis

	SI	AD	RI	Ca	SP	Pr	Se	Te	AR	PR	AA	RE	OC	Total number
SI	X	12	10	1	6	3	3	3	3	17	3	13	9	83
AD	-	X	9	.	.	2	3	3	.	3	3	.	.	23
RI	-	-	X	.	.	3	3	3		1	2	.	.	12
Ca	-	-	-	X	2	.	.	.	2	1	2	.	.	7
SP	-	-	-	-	X	.	.	.	2	1	2	.	.	5
Pr	-	-	-	-	-	X	4	4	.	.	1	.	.	9
Se	-	-	-	-	-	-	X	4	.	2	1	.	.	7
Te	-	-	-	-	-	-	-	X	.	2	1	.	.	3
AR	-	-	-	-	-	-	-	-	X	.	.	.	.	0
PR	-	-	-	-	-	-	-	-	-	X	1	10	9	20
AA	-	-	-	-	-	-	-	-	-	-	X	.	.	0
RE	-	-	-	-	-	-	-	-	-	-	-	X	11	11
OC	-	-	-	-	-	-	-	-	-	-	-	-	X	0

Table 2

Differences between the times of meridian transit of Sirius and Procyon for the year 1686

Day	Month	T (Sirius)	T(Procyon)	ΔT (sec.)
23	1	10h 7’ 58”.5	10h 59’ 10”	3071.5
18	2	8h 24’ 33”.5	9h 15’ 47”	3073.5
7	3	7h 16’ 57”.5	8h 8’ 12”.25	3074.75
8	3	7h 12’ 59”.5	8h 4’ 13”.5	3074.0
9	3	7h 9’ 1”.25	8h 0’ 14”.5	3073.25
28	3	6h 3’ 24”.0	6h 54’ 37”.0	3073.0
4	4	5h 35’ 14”.5	6h 26’ 27”.5	3073.0
5	4	5h 31’ 13”.0	6h 22’ 26”.0	3073.0
11	4	5h 58’ 13”.75	5h 7’ 0”.75	3073.0
13	4	5h 3’ 57”.0	5h 55’ 9”.5	3072.5
14	4	4h 59’ 54”.5	5h 51’ 7”.0	3072.5
15	4	4h 55’ 51”.5	5h 47’ 6”.0	3074.5
23	4	4h 23’ 38”.75	5h 14’ 52”.0	3073.25
30	4	4h 0’ 39”.0	4h 51’ 52”.0	3073.0
13	5	3h 8’ 48”.25	4h 0’ 1”.25	3073.0
28	5	2h 8’ 56”.0	3h 0’ 8”.0	3072.0
1	6	1h 52’ 55”.0	2h 44’ 7”.0	3072.5
			Mean	3073.073
			σ	0.534

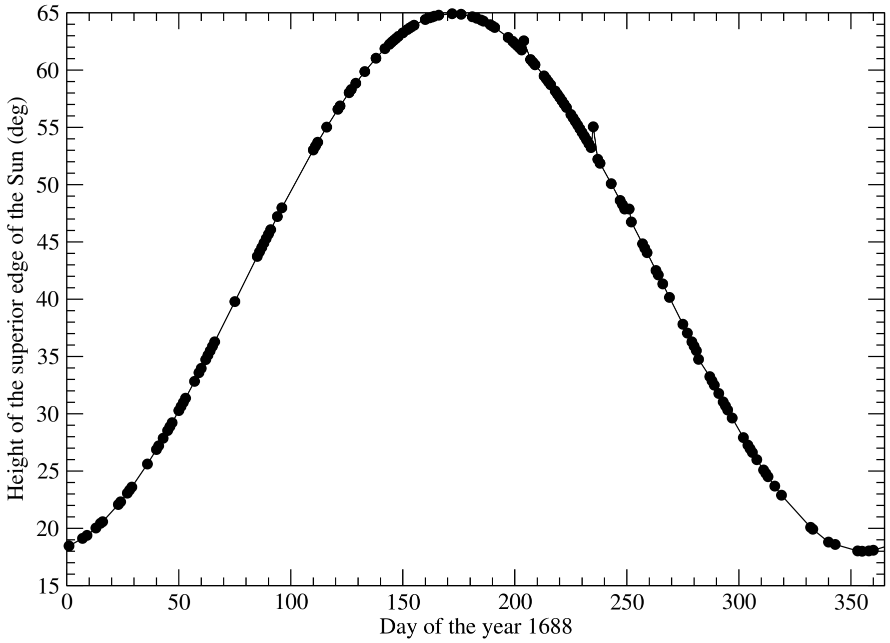


Fig. 14 – Variations of the height of the superior edge of the Sun during the meridian transit for the year 1688.The curve is an empirical polynomial fit.

enables us to avoid the significant drifts of the mechanical clock used for the timing, typically of the order of a few seconds, as those described in Sect. 2. Moreover, the larger the number of intra-night inter-comparisons for a given pair of stars the better are the estimates of the differences $\Delta\alpha$ and $\Delta\delta$, for obvious statistical reasons. The brightest star of the sky Sirius was by far the most used for transit inter-comparisons with other stars. Its enormous advantage lies in that it was observed by La Hire even at day time, during the whole year, thanks to its brightness. In Table 1, we show the number of intra-night inter-comparisons for each pair of stars amongst a set of 13 bright stars often observed by La Hire during the year 1686. We note that Sirius offers a substantial set of 83 inter-comparisons, which is slightly less than the 97 inter-comparisons coming from the other pair of stars. The star with the largest number of inter-comparisons with Sirius is Procyon, the eighth brightest star in the sky, with 17 opportunities for the sole first six months of the year 1686. Procyon is close to Sirius in the celestial sphere, this explains the large number of inter-comparisons. In Table 2, we show each of them with the corresponding values of the difference between transit time. We observe that all these values are in very good agreement, with a minimum at Δ T = 3071.5 sec. and a maximum at Δ T = 3074.75 sec., a mean value at Δ T = 3073.07 sec., and a standard deviation $\sigma = 0.534$ sec., that is to say roughly 1/2 sec. This result is remarkable as given the relative lack of precision of both the mechanical clock and the astrometric device of the refractor used. Such inter-comparisons might be of great interest to check the positioning of the equator of the date (in that case of the year 1686) with respect to the equator of the reference epoch J2000.0 which is the conventional one in modern astronomy. In other words, the difference of time transit between various pairs of stars is directly dependent on the location of the equatorial plane in the celestial sphere; thus by multiplying the inter-comparisons it might be possible to determine accurately this location and to deduce the exact motion of the celestial equator over three centuries ago, due to the precession of equinoxes. This motion should be compared with the motion deduced from modern theories of the positioning of the pole undergoing the combined precession-nutation motion

6. OBSERVATIONS OF THE MOON AND THE PLANETS

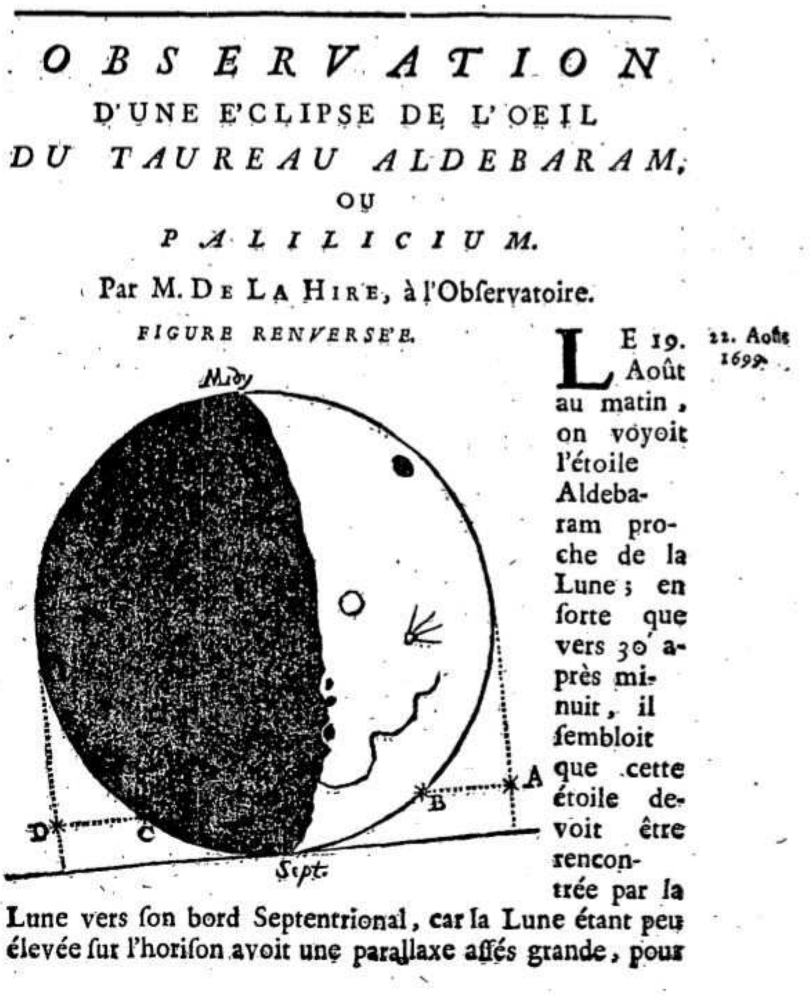
In addition to a systematic account of the solar transits and a casual report of the transit of the stars, La Hire was deeply involved in the observations of the positions of the five known planets Mercury, Venus, Mars, Jupiter and Saturn, as well as those of the Moon. With regards to our satellite, numerous reports were similar to those related to the Sun, *i.e.* the exact time of meridian transit of both the western and eastern edges as well as the height of both the inferior and superior edges during the transit, from which he could deduce two associated parameters which are the horizontal and vertical angular diameters. These reports were fundamental to refine at best his own lunar ephemeris displayed for instance in his *Tables Astronomiques*. The smallest the difference between the orbital characteristics scheduled by the tables and the observational determinations, the highest the degree of confidence in the tables. In that domain, a challenging topic was the exact prediction of the timing and of the geometry of the lunar eclipses. A perfect illustration is brought by the December 8th, 1703 partial solar eclipse, that happened just before sunset. Ephemerides of this epoch diverged about the real occurrence of this eclipse. In the *MARS 1703* La Hire writes that “ [...] some tables gave this eclipse, others did not. As for mine, they recorded it rather in conformity with the reality”.

The positions of the Moon, the planets, and the stars were recorded by La Hire for more than 20 years, leading to a precise model of their motion, both in celestial latitude and longitude, in other words, in right ascension and declination. Another important event is the transit of a bright star behind the Moon. A good example is the transit of Aldebaran behind our satellite, on August 19st,1699 reported by La Hire in *MARS 1702*, as shown in Figure 15. In his preface of *Tables Astronomiques*. La Hire explains that the great advantage of Venus lies in the fact that this planet can be viewed during the daytime, and in particular when it is very close to the Sun, near the conjunction, even at only 1° angular distance from our star, which corresponds to no more than twice its angular size. Therefore in that case, it is possible to carry out differential astrometry, *i.e.* to determine with great accuracy the positional difference between the Sun and Venus, as well as to increase the number of positional accounts of this planet during the daytime. La Hire mentions in the preface of the *Tables astronomiques* that the motion of Venus as well as the other planets does not fit exactly an ellipse, as it was postulated by Kepler for instance in his famous *De Motibus Stellae Martis* in the case of Mars (Kepler, 1609). Of course we know presently that this empirical conclusion finds its origin in the gravitational perturbations of the other planets, which change slightly and gradually the characteristics of the osculating ellipse to which the planetary motion can be fitted at any time. This will conduct La Hire to investigate the exact determination of what he calls "the centre equation" which is a geometrical empirical quantity enabling to insure the fit. An important remark is that Newton published the first edition of his famous work *Philosophiæ Naturalis Principia Mathematica* in 1687, that is to say 4 years after the beginning of La Hire's campaign of observations, and the second edition was published in 1713, that is to say 5 years before the end of this campaign. Therefore if La Hire had a direct access to the *Principia*, as it could be the case if the diffusion of Newton laws and calculations were larger, he would have been able to understand the origin of the difference between the true motion of the planets and their elliptical approximation.

7. REPORT OF LA HIRE OBSERVATIONS IN LE MONNIER'S *HISTOIRE CÉLESTE*

Pierre-Charles Le Monnier (1715–1799) is one of the leading astronomers of the 18th. century. Besides personal works, whose the most famous were the studies about refraction and the establishment of tables of the Sun, he was concerned with recording the works of his predecessors as well as his contemporary astronomers. Laudatory comments on La Hire contribution to astronomy are found in his *Histoire Céleste*, published in 1741, that is to say 20 years after La Hire's death. This book can be considered as an exhaustive compilation of the works carried out by leading astronomers of the end of the 17th and the beginning of the 18th century, mainly Cassini, Picard, La Hire, but also Røemer, Flamsteed, Newton, etc .

Amongst his comments in the preface of *Histoire Céleste* Le Monnier writes that La Hire has carried out nearly 40 years of astronomical observations which have a great advantage upon the previous ones : the right ascensions of the celestial bodies have been determined with a wall (fixed) meridian circle starting from April 1683. Le Monnier also reckons that the lunar observations in La Hire's registers, and mainly those for the year 1686, must be considered as the most accurate of that time to improve the theory of our satellite, whose orbital motion is so difficult to model. His analysis concerns the period 1678–1686. Therefore it is common with the analysis done in this paper for the period 1683–1686.



OBSERVATION
D'UNE E'CLIPSE DE L'OEIL
DU TAUREAU ALDEBARAM,
OU
PALILICIUM.
Par M. De La Hire, à l'Obſervatoire.

FIGURE RENVERSE'E.

22. Août 1699.

Le 19. Août au matin, on voyoit l'étoile Aldebaram proche de la Lune; en ſorte que vers 30′ après minuit, il ſembloit que cette étoile devoit être rencontrée par la Lune vers ſon bord Septentrional, car la Lune étant peu élevée ſur l'horiſon avoit une parallaxe aſſés grande, pour

Fig. 15 – La Hire's drawing showing the transit of the bright star Aldebaran behind the disk of the Moon.

A major issue of Le Monnier's analysis concerns the refraction. In particular, he mentions that "nobody ignores that astronomical refractions have always been one of the major obstacles to the progress of astronomy & that the best Tables which have been published since 60 years ago are different from one to the other by a rather important quantity". As an example, he explains that when we compare the tables given by Cassini and those given Flamsteed, we find a difference of nearly 1', exactly 55", for a height of 10°, and the difference is still 10" in the direction of the north celestial pole. Le Monnier also investigated the tables of refraction of La Hire in his *Tables Astronomiques* and found that the quantity of refraction for heights ranging between 40° and 50° are larger than those given by Cassini's tables by 12", which is considerable, as given the precision of the measurements of the epoch, of the order of 1". On this subject, it should be interesting to investigate if the disagreement between the two tables should potentially be explained by the fact that the two authors neglected the nutation effect, which was unknown at their epoch. Indeed, as it was explained above, the nutation in obliquity is characterised by a dominant sinusoid with amplitude $\Delta\varepsilon = \pm 9$" and with an 18.6 year period. Therefore the sinusoid affects the determination of the height of any star by its own amount. Therefore, if Cassini and La Hire established their refraction tables at an epoch corresponding to a different phase of the nutation cycle, this should explain the difference of 12". We will further investigate this possibility in future studies.

In *Histoire Céleste*, Le Monnier mentions another significant phenomenon which has to be taken into account : the aberration of light, which is a classical correction (see for instance Danjon (1967)) due to the translation motion of the Earth along its orbit. As for the nutation, this phenomenon was discovered by Bradley from continuous observations of the star γ Draconis done at Molyneux (Bradley, 1728), that is to say only 10 years after La Hire's death and 13 years before Le Monnier's publication. Thus Le Monnier studied meticulously the values recorded during the year 1683 by La Hire of the meridian height of Sirius, the brightest star, to check if these values could be affected by the aberration. He noted that the values given by La Hire are $24°52'47$" on April 8th, $24°52'40$" on April 14th, $24°53'0$" on October 1st. This big difference over a 6 months interval can be attributable to aberrations. Nevertheless, theoretically there should not be height differences between the beginning of January and end of June, for which the amount of aberration is the same. This is contradicted by La Hire's value of $24°53'0$" obtained on January 12th and values of $24°52'38$" and $24°52'32$" found respectively on June 22nd and June 25th. Here also, the effect of the nutation in obliquity, which was unknown at the time of Le Monnier's observations, could play a significant role in the discrepancies as well as the uncertainties related to the amplitude of the refraction effect. Here also a modern treatment of La Hire's measurements including very accurate models of the various phenomena involved, such as precession, nutation, aberrations, and refraction would be of great interest.

8. CONCLUSION

In this paper, we have made a general overview of La Hire's astronomical registers corresponding to the period 1683 – 1718, that is 35 years of continuous observations carried out on a daily basis with a fixed meridian circle installed along the wall of the Paris Observatory. Thanks to clock calibration with the meridian transits of bright stars such as Sirius, we could determine exactly the drift between the mechanical clock used by La Hire for his transit timings, thus showing that this drift did not exceed ±10 sec. per day, which constitutes a performance, less than thirty years after the construction of the first mechanical clock by Christiaan Huygens (1629–1695).

Moreover, we have emphasised the advantages which can be found in the analysis of about seven thousand records of meridian transits of the Sun. Once the combined effects of refraction, precession, nutation and aberration be duly taken into account using modern calculus, it might be possible to confront La Hire's observations of the equation of time, of the meridian height of the Sun, as well as of the transit duration, with the values obtained from modern ephemerides. From that O-C (Observed - Calculated) data, it will be possible to constraint these ephemerides, as well as the value of fundamental parameters such as the obliquity, the exact time of solstices and equinoxes. At last, we have shown how the precise timing of the transit of stars may lead to a determination of the positioning of the celestial equator at La Hire's epoch which can then be confronted with modern determinations of this positioning taking into account the combined precession-nutation effects.

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