THE LIGHT-TIME EFFECT IN ASTROPHYSICS
Causes and cures of the $O - C$ *diagram*
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Ole Roemer and the Light-Time Effect

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Abstract. We discuss the observational background of Roemer's remarkable hypothesis that the velocity of light is finite. The outcome of the joint efforts of a highly-skilled instrumentalist and a team of surveyors driven to produce accurate maps and technically supported by the revolutionary advancements in horology, illustrates the synergy between the accuracy of the O and the C terms in the $O - C$ concept which led to one of the most fundamental discoveries of the Renaissance.

1. Olaus Roemer (1644–1710)

Ole Roemer was born in Aarhus (Jutland) in 1644. One of the prime scientific challenges of his times was to find a direct proof for the Copernican hypothesis through the detection of stellar parallax. As such, Roemer tried to measure parallaxes of fixed stars by intensive observation and by reducing observational errors through technically innovative instrumentation.

Roemer intensively contributed to the solution of several technical and scientific issues and introduced many new ideas to the instruments of his time. He had a keen eye for instrumental accuracy, and he worked on the quantification of ambient temperature effects on instrumental errors. To do this properly, he even had to define a temperature scale himself, and as such he laid the foundations of the Fahrenheit scale.

In 1681, summoned by Christian V, king of Denmark, he became royal mathematician and professor of astronomy at the university of Copenhagen. From 1688 on, Roemer accepted several important administrative functions, such as waterworks engineer, chief tax assessor, chief of police, mayor of Copenhagen, senator and head of the state council.

Copenhagen Observatory, constructed in 1642 by king Christian IV, was one of the oldest observatories in Europe, and was built in the form of a tower over 35-m high and 15-m diameter (Fig. 1). The observing platform is accessible by a helicoidal ramp on which – according to legend – Peter the Great of Russia rode a horse alongside his wife, who took a carriage. The unusual building is the oldest such structure in Europe, and is still one of Copenhagen's tourist attractions. Few scientific works of Roemer survived because almost all of his original writings were lost in 1728 when Copenhagen Observatory was destroyed by fire. One notorious manuscript survived: the *Triduum*, containing data from three days of observations at his private observatory *Tusculanum* located 20 km north of Copenhagen. This manuscript is of great value, since it gives ample insight in Roemer's dedication to observational accurateness. The reason why he preferred to work from his private observatory may very well be hidden in his letter to Gottfried Wilhelm Leibnitz dated 15 December 1700 (See 1903):

> "I differ very widely from those who have hitherto decked out observatories more for show than for use, accomodating the instruments to the buildings rather than the buildings to the instruments."

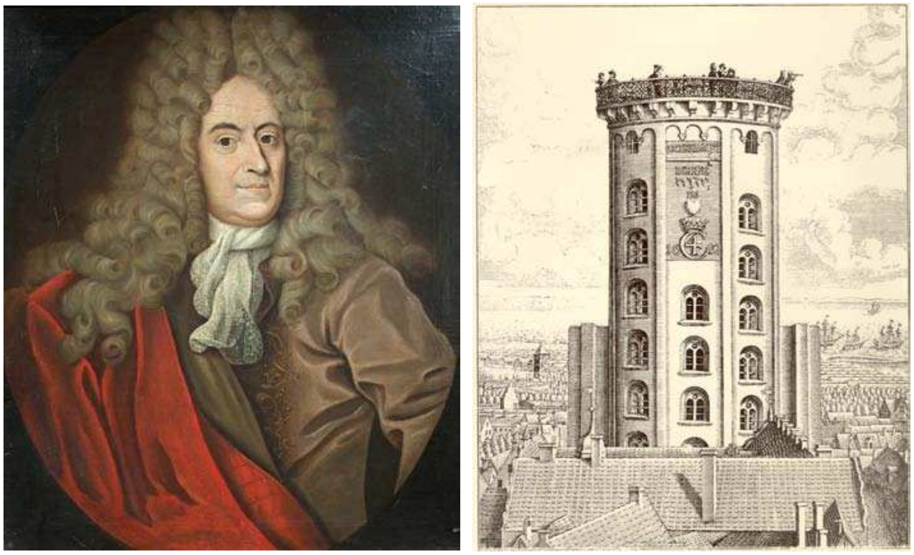

Figure 1. *Left:* Portrait of Ole Roemer. The original is at the Rundetårn Museum in Copenhagen. *Right:* Copenhagen Rundetårn Observatory in 1657.

2. Picard, Cassini and the French Académie Royale des Sciences

The French Academy was founded under the auspices of Louis XIV in 1666 with as one of its direct practical purposes the correction and improvement of maps and nautical charts (see Cohen 1942). One of the pioneering mapmakers was the French astronomer Jean Picard (1620–1682) who worked with Giovanni Domenico Cassini (1625–1712), a professor at the University of Bologna and one of the first members of the *Académie Royale des Sciences*. In 1669 Cassini moves to Paris where he observes under the auspices of the *Académie*.

In 1664 Cassini explains how simultaneous observation of a same satellite of Jupiter from two different locations will lead to the difference in longitude between these places. Simultaneity, though, implies an accurate measurement of time. Grimbergen (2004) recognizes two important periods in the evolution of mechanical time measurement: the period 1300–1657 using verge escapements, and the post-1657 era using a resonant system as regulator. It was Christiaan Huygens (1629–1695) who introduced the pendulum in 1657 and balance wheel with spring in 1669. Cassini's method was consequently applied to surveying and led to new maps (see the significant differences in the coastlines in Fig. 2), although true geodesic methods possess superior accuracy. By 1680, satellites of

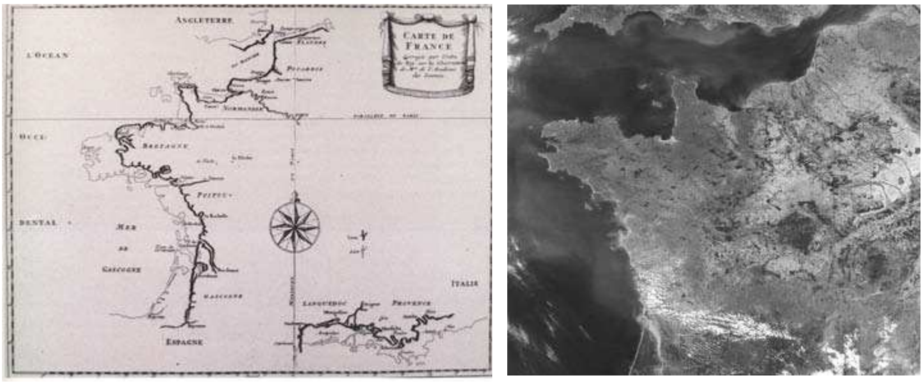

Figure 2. *Left:* Carte de France, 1729 *"Corrigée par Ordre du Roy sur les Observations de* M^{rs} *de l'Academie des Sciences"*. The thin line was the former outline, the heavy shaded outline is based on a manuscript by Philippe de la Hire of 1684 and encompasses a territory that is 20% smaller than the former. *Right:* satellite picture of the same region.

Jupiter became the official method of longitude determination by the Académie. The method was not practical at sea, however: long focal distances were needed, and long telescopes are not compatible with the ship's motions.

3. A Giant Universal Clockwork

Table 1. Galilean satellites: semi-major axis a [km], light-travel time in Jupiter system $2a$ [sec], period P [days], magnitude and diameter D [km].

	Name	a	$2a$	P	mag	D
I	Io	421800	2.8	1.77	5.0	3643
II	Europa	671100	4.5	3.55	5.3	3122
III	Ganymede	1070400	7.1	7.16	4.6	5262
IV	Callisto	1882700	12.5	16.69	5.7	4821

The four brightest satellites of Jupiter (Table 1, see also Fig. 3) were discovered by Galileo in 1610, and were intensively observed in the subsequent century[1]. Pierre-Simon de Laplace discovered during the late 1700s that the orbital periods of Io, Europa, and Ganymede are nearly in a perfect 1:2:4 ratio. The satellites undergo eclipses in the planet's shadow cone, and this leads to times of immersion and emersion; there are also transits and shadows projected on Jupiter's disk. Galileo proposed the idea of using Jupiter and its four

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[1] There are 57 other moons that have been discovered around Jupiter. All of them are smaller than the Galilean Satellites, and most of them are the size of small asteroids.

"Medicean" satellites[2] as a giant clockwork on the sky, indicating the reference time to any observer in the northern or southern hemisphere. This became one of the best methods for determining longitude from almost anywhere in the world: timings of telescopic observations of Jupiter's moons are compared with a Table of calculated positions as a function of Paris local time. The jovian satellites, so to speak, became a clock to read universal time – that is, Paris time.

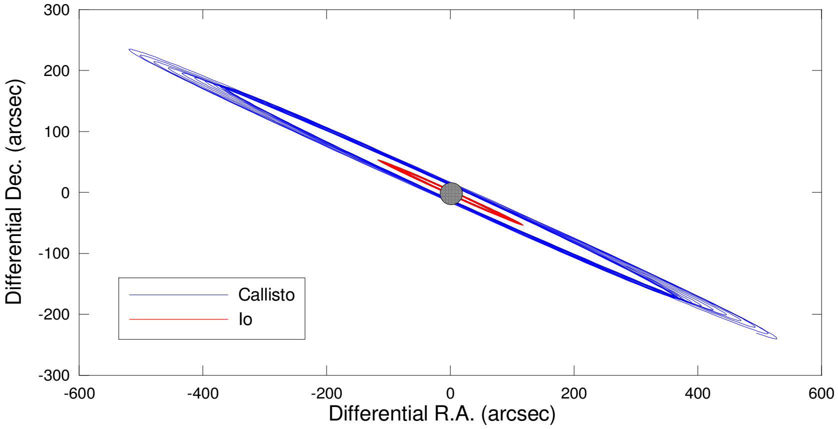

Figure 3. Motion of Jupiter's first and fourth satelites in differential equatorial coordinates for May 2004.

In August 1671 (70 year's after Tycho Brahe's death), Jean Picard traveled to Denmark, with the purpose of comparing Tycho's observational data with new data obtained by Cassini in Paris. So, he went to the island of Hven to determine the exact geographical position of Tycho Brahe's Uraniborg observatory. He was assisted by the young Ole Roemer. The expedition by Picard to Uraniborg was covered by Cassini in Paris, who observed five eclipses simultaneously. On 25 October 1671 and 4 January 1672, a same immersion of Io was observed from Paris and from Uraniborg, leading to a longitude difference of 42 minutes (Lévy 1978).

In 1672, at the age of 28, Roemer follows Picard to Observatoire de Paris (founded 5 years earlier), where he worked during about a decade and where, in 1676, he put forward the hypothesis that the speed of light is finite.

4. Roemers Discovery

In 1668, Cassini had published Tables of eclipses of jovian satellites: the *Ephemerides Bononiensis Mediceorum Siderum*, which for the first time contain the method of determination of differential longitude by simultaneous timing of eclipses.

It was in comparing the results of observations with the tabulated values that Roemer came upon the fact that Io eclipses arrived too early before opposition,

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[2] As called by Galileo, in the hope of gaining patronage of the Grand Duke Cosimo II.

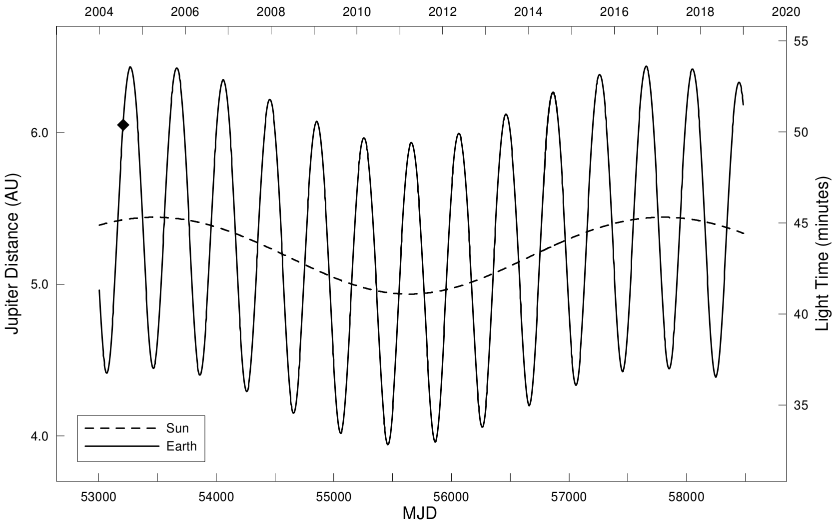

Figure 4. Relative distance of Jupiter with respect to Sun and Earth 2004–2010 (left axis in AU, right axis in minutes). The diamond indicates 21 July 2004, the day this talk was given. The eccentricity of the Jupiter orbit ($e = 0.048$) causes a range in distance of 76 million km. The distance from Jupiter to Earth varies from 588.4 to 968.5 million km with a synodic period of 398.88 days $\sim$ 13 months. Hence a 12-year component and a 1.09-year periodicity in the $O - C$ diagram is to be expected.

and too late after opposition[3]. The intervals between successive eclipses are very uniform near opposition because the distance Jupiter – Earth is fairly constant during this time (see Fig. 4). Most of the discrepancy occurs during the times when the distance between Jupiter and the Earth is changing most rapidly, which

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[3] From Earth one can see either immersion or emersion, not both at the same time since Jupiter's disk blocks the view.

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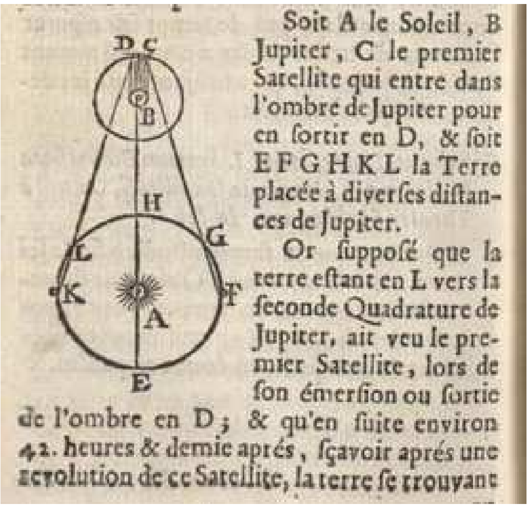
Figure 5. *Journal des Sçavans*. *Left:* Part of the collection at the library of Vienna University Observatory. *Right*: frontispiece (1675).

is when the Earth-Sun axis is nearly perpendicular to the Jupiter-Sun axis. At one of these positions the Earth is moving almost directly toward Jupiter, and at the other it is moving almost directly away from Jupiter: at quadratures the change in distance Earth-Jupiter is almost entirely due to the Earth's orbital motion. Roemer thus noticed that the times of eclipses of Jupiter's satellites varied periodically over the year by ±8 minutes[4].

Roemer explains the dichotomy by assuming that light traveled at finite speed, a bold idea that was in contradiction with the opinions of Descartes (and Aristotle). On 22 September 1676 Roemer presented his conclusions on the propagation of light before the Académie des Sciences, and on 7 December 1676 he publishes his paper *Demonstration touchant le mouvement de la lumière* in *Journal des Sçavans* (Figs. 5 and 6):

> *"Et parce qu'en 42 heures & demy, que le Satellite employe à peu prés à faire chaque revolution, la distance entre la Terre & Jupiter dans l'un & l'autre Quadrature varie tout au moins de 210. diametres de la Terre, il s'ensuit que si pour la valeur de chaque diametre de la Terre, il faloit une seconde de temps, la lumiere employeroit* $3\frac{1}{2}$ *min. pour chacú des intervalles GF, KL, ce qui causeroit une differénce de prés d'un demy quart d'heure entre deux revolutions du premier Satellite, dont l'une auroit este observée en FG, & l'autre en KL, au lieu qu'on n'y remarque aucune difference sensible."*



Soit A le Soleil, B Jupiter, C le premier Satellite qui entre dans l'ombre de Jupiter pour en ſortir en D, & ſoit EFGHKL la Terre placée à diverſes diſtances de Jupiter.

Or ſuppoſé que la terre eſtant en L vers la ſeconde Quadrature de Jupiter, ait veu le premier Satellite, lors de ſon émerſion ou ſortie de l'ombre en D; & qu'en ſuite environ 42. heures & demie aprés, ſçavoir aprés une revolution de ce Satellite, la terre ſe trouvant

Figure 6. Roemer diagram as published in the *Journal des Sçavans*.

Roemer knew that during one orbital period of Io (∼ 42.5 hours) the Earth-Jupiter distance changes by at least 210 Earth diameters, and he thus conjectures: *if for the account of every diameter of the earth there were required a*

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[4] It is not a trivial matter to find out whether the underlying data are from Roemer, or were obtained by him in collaboration with Picard (for a discussion, see Débarbat 1978).

second of time[5], *the light would take* $3\frac{1}{2}$ *minutes for each of the intervals GF, KL, which would cause a difference of nearly 'a half quarter of an hour' between subsequent revolutions of the first satellite at both quadratures.* Differentiating between the observations at quadrature, an $O - C$ of 7 minutes was never measured and hence light needed less than one second to traverse one Earth Diameter.

5. Cassini's Objections

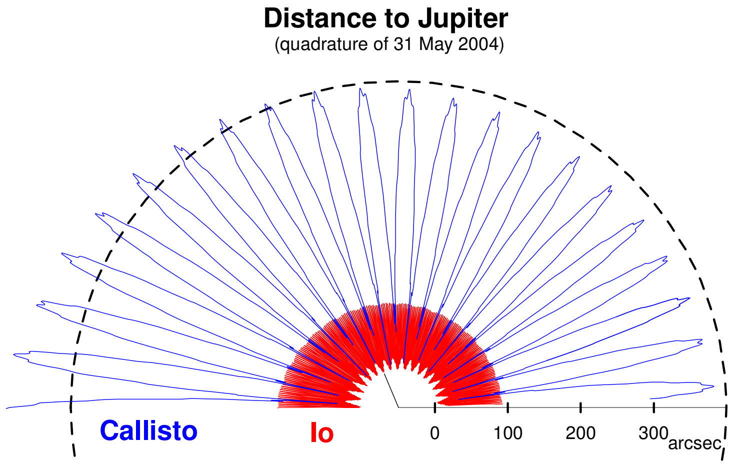

Figure 7. Distance to Jupiter of Io and Callisto, quadrature of 31 may 2004.

But the observations collected in Paris revealed that only the calculated predictions for the *first* Iovian satellite could be adequately used: the question simply was why do the three other Galilean satellites not show the same time inequality that Roemer noticed for the first? Cassini thus accepted the time retardation as a principle, but could not agree with the numerical value since different satellites presented different results. The reason for the discrepancies is due to the fact that the motions of the three other satellites are affected by complicated mutual perturbations, see an aspect of this effect in Fig. 7.

6. The Velocity of Light

Though many textbooks state that Roemer was the first to measure the velocity of light (see also Fig. 8), he did not explicitly give its value in distance units per second: his major conclusion was a qualitative one: that the speed of light is finite.

Roemer assumed an Earth Diameter of about 13300 km. In 1672, when Mars was in opposition, Cassini, Picard and Richer carried out observations of Mars simultaneously from Paris and Cayenne, and determined a parallax of about

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[5] thus assuming the speed of light is approximately $0.04c$.

15″ and thus a distance $D = 90,000,000$ km. Kepler's third law then yields an estimate of the astronomical unit (AU):

$$\begin{aligned} \frac{(1)^2}{(1.88)^2} &= \frac{(AU)^3}{(AU+D)^3} && (1) \\ (1.88)^2 &= (1+\frac{D}{AU})^3 && (2) \end{aligned}$$

and hence $1AU \sim 143,000,000$ km, which could have led him to an estimate of the velocity of light of about 200,000,000 km s^{-1}.

7. Roemer's Work and $O - C$ Basics

Roemer's data covered a substantial time base: expressed in cycles, the satellite Io completes more than 100 cycles every six months (the periodicity seen in Fig. 4), excluding any cycle-count errors. Several reference phases are possible: eclipses, immersions, emersions,…). Jupiter – the universal clock with four hands – could not be used as four independent clocks since only Io revealed correct time delays: as long as the underlying model for C remained simple, even the most precise timings of the key phenomena of the remaining three moons could never produce an $O - C$ diagram that could lead to confirmation of the correct hypothesis of the time delay. But even with a complete orbit calculation, Callisto would not be a very good choice because its orbit is relatively wide, which can lead to the absence of eclipses for long periods of time (see Fig. 7).

The point is also that the interpretation of the $O - C$ fluctuations is not always obvious: Roemer's discovery led to the necessity of the equation of light, but his hypothesis led to controversies with Cassini and other contemporaneous colleagues because the issue of a finite speed of light with such a high velocity was almost unacceptable.

8. Epilogue

The story of Roemer's unexpected discovery is a textbook example of proper $O - C$ analysis: optimising observational precision in combination with increasingly

Figure 8. Ole Roemer plaque at Paris Observatory.

accurate computational Tables, the procedure leads to the unexpected discovery of a fundamental physical concept. And as Montucla (1758) points out, a long time baseline and careful observations are a most necessary condition:

> *"Des observations continuées long-temps et avec soin, ont ordinairement l'avantage de faire apercevoir des phénomènes dont on n'avoit encore aucun soupçon; souvent même il arrive que ces observations conduisent à une découverte plus intéressante que celle dont on cherchoit à s'assurer par leur moyen.*[6]

Acknowledgments. Thanks to Jørgen Otzen Petersen (Copenhagen Observatory) for donating a printed reproduction of an engraving of Copenhagen's Rundetårn (Fig. 1), and Ole Henningsen of the Rundetårn Museet Copenhagen for providing a copy of one of the best Roemer portraits. The hospitality of Michel Breger and Maria Firneis during the consultations at Vienna Observatory's library and the permission to reproduce the 1675 frontispiece of *Journal des Sçavans* (Figs. 5 and 6) is greatly appreciated.

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Vogt: I was not aware that Roemer, in fact, did not really measure the speed of light. But which value for the AU was used till Richer and Cassini's result of 1672?

Sterken: Even Copernicus and Kepler did not know the numerical value of the astronomical unit, which was a much sought-after parameter since Aristarchus' times. Only since the 17th-century Mars opposition and the subsequent Transits of Venus, a more or less accurate numerical value was available.

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[6] Observations over *long time intervals carried out with care*, normally have the advantage to make appear totally unexpected phenomena; it even occurs that these observations lead to a discovery that is more interesting than the one for which the observations were made for."

Izold Pustylnik and Theodor Pribulla