

## **Ole Roemer's Speed of Light: Recreating the Unintentional Discovery**

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### **Abstract**

Before the year 1676, the speed of light was thought to be an unmeasurable, infinite quantity in the field of physics and astronomy. It had been proposed briefly by Jean-Dominique Cassini that it was a finite value, rejected, and then adopted once more by Ole Roemer from the same staff while Cassini was at the Paris Observatory. The theory used by Roemer proved conducive, yet not as accurate as if it had been recreated using modern knowledge and astronomical data. This experiment aims to combine Ole Roemer's theory with the astronomical technology of today to determine the finitude of the speed of light. In order to fulfill this, observations are made using both the open-source astronomy software Stellarium to take simulated data of 40 orbits of Io around Jupiter as the Earth moves counterclockwise in its orbit around the Sun, and a SeeStar S50 smart telescope to observe Io as it orbits around its planet in the months of December 2024, March, and April 2025. As the Earth moves towards Jupiter, the observed orbits of Io become shorter, due to the light reflected off the moon and its planet that's coming towards us having a decreasing distance it needs to travel. On the opposite side of Earth's orbit, moving away from Jupiter, the orbits of Io become longer due to the light needing to travel an increasing distance from us as observers. This change in the orbit of Io proves that the speed of light is finite, as it would remain unchanged should it be infinite.

*Keywords:* Astronomy, Io, Jupiter, Galileo Galilei, Jean-Dominique Cassini, Ole Roemer, Stellarium, SeeStar S50

## **Ole Roemer's Speed of Light: Recreating the Unintentional Discovery**

The word Serendipity was first used by the author Horace Walpole in 1754 inspired by heroes from a Persian fairy tale, and is currently defined as “the faculty or phenomenon of finding valuable or agreeable things not sought for” (Merriam-Webster, n.d.). While most scientific discoveries are purposeful experiments designed piece by piece, rejected and altered and accepted, quite a few discoveries in scientific history have been serendipitous. The inventor Richard T. James dropped a tension spring when he was experimenting with them to create a suspension system for naval instruments, and the strange motion the spring demonstrated inspired the creation of the Slinky, a beloved children’s toy used today to explain the dynamics of waves in physics. When working with a radio telescope originally designed to detect signals that bounced off of balloon satellites, astronomers Arno Penzias and Robert Wilson heard an odd and inexplicable background noise that resulted in the discovery of the Cosmic Microwave Background radiation, a detectable imprint of the beginning of the universe (Perimeter Institute, 2018). Among these serendipitous breakthroughs in scientific history lies a fundamental constant of nature: the speed of light.

### **The Speed of Light**

Philosophers and astronomers originally thought that light traveled instantaneously, or at an infinite and unfathomable speed. The theory was not doubted until the late 1630s when Italian astronomer Galileo Galilei began to wonder whether or not the velocity of light could actually be measured. In an experiment with two of his peers serving as observers, Galilei placed an observer a few braccia – a Florentine unit of measurement in which a single braccio is about 60 centimeters today – away from the other and provided them both with illuminated lamps. Both observers would cover their lamps, and as one began the experiment by uncovering his lamp, the

other observer would uncover his own lamp when he could see the light from his partner (Foschi & Leone, 2009). In theory, Galilei would be able to record a time difference between the two lamps lighting up as light would travel from one man to the other. In practice, the speed of light was simply too fast for the time difference to be caused by anything other than either of the men's reaction speed; As we now know today, light travels at a speed so fast that – over such a short distance – it cannot be perceived by the human eye. After the attempt by Galileo Galilei to measure a speed of this thought-to-be infinite concept, no other pursuit would gain traction until Ole Roemer at the Paris Observatory from the 1660s to the 1670s. Despite its result, this pursuit did not begin with the desire for light's speed.

While exploring or navigating on the ocean, a sailor can determine their latitude by measuring the angle between the north star Polaris and the horizon, or the Sun and the horizon so long as it is solar noon – in which the Sun has reached its highest point in the sky – and the date is known, thus the proper calculations can be made. Longitude is a much more complicated endeavor, and a technique to measure it during navigation was highly sought after in the 17<sup>th</sup> century. The measurement and calculation of longitude requires a clock that enables a navigator to compare their current time to the time in a place with a known longitude, such as the Paris Observatory (Soter & Tyson, 2000). When Galileo Galilei first observed the brightest moons of Jupiter – Io, Europa, Ganymede, and Callisto – he made a note in his records that they could possibly be used as a universal clock so long as their orbital periods were widely known. Even though Galilei did not investigate to find out if his theory had any validity, it was this theory that inspired Italian-French astronomer Jean-Dominique Cassini to take detailed records of Io's orbits around Jupiter, and eclipses with the planet, and publish tables for the scientific community to reference. During his comprehensive observations of Io's orbit, Cassini noticed a discrepancy in

the orbits of Io as Earth moved towards Jupiter and as Earth moved away from Jupiter. He briefly entertained the idea that this repetitive inconsistency could have been caused by a finite speed of light, but later rejected the thought and continued with the goal of determining whether or not Io and Jupiter could be used by navigators worldwide to determine longitude. Cassini's original objective, too, was eventually thrown out on the account of limited frequency; Because of the duration of Io's period, the moon would take too long to complete one orbit around its planet when a sailor would need to view an entire orbit to calculate longitude. They would need to stay in exactly the same location for over a day and a half before a navigator could estimate the value and move on. On the other hand, had Io's eclipses with Jupiter been used for a clock, they were still too infrequent even when they took less time to observe than a full orbit (Bobis & Lequeux, 2008).

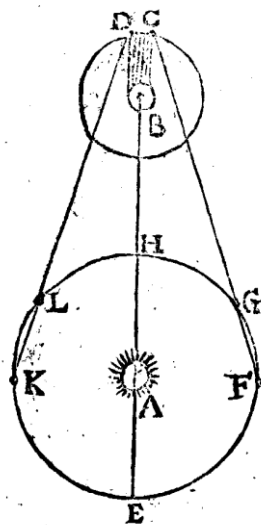
At the same time that Cassini worked at the Paris Observatory, another member of the staff that made the observations to produce the most accurate tables for Jupiter and its satellites at the time was Danish astronomer Ole Roemer. After Cassini rejected his own initial theory that the variation in the orbits of Io around Jupiter could be due to the speed of light being a finite value and changing based on where the Earth was in reference to Jupiter, Roemer adopted the theory as his own to continue the investigation during his studies (Van Helden, 1983).

### **Ole Roemer's Experiment**

Ole Roemer began his investigation into the finitude of the speed of light by observing the orbit and eclipses of Io as it revolves around Jupiter. He created a diagram to support his explanations when he published his observations of Io and Jupiter in the December 7<sup>th</sup>, 1676, issue of the *Journal des Sçavans*, which can be seen below in Figure 1.

### **Figure 1**

The diagram drawn by Roemer to explain his observations of Io's orbit around Jupiter throughout the revolution of Earth around the Sun. The Sun is marked by A, Earth's orbit marked by letters EFGHLK going counter-clockwise, Jupiter marked by B, and Io's disappearance and re-emergence from behind Jupiter by letters DC (Römer, 1676).



In his publication, Roemer describes his observation of the revolutions of Io as the Earth orbits counterclockwise around the Sun, passing from point F to point G, then point L to point K. At each point on either side of the Sun, FG and LK, 40 revolutions of Io around Jupiter were observed and recorded. Roemer was able to note the completion of an orbit around Jupiter when Io disappeared behind the planet at point D, then re-emerged at point C, an act he knew would only occur once per revolution. The observation of each portion of the Earth's orbit showed that as the Earth moved towards Jupiter, the revolution of Io appeared to take less time, and as the Earth moved away from Jupiter, the revolution of Io appeared to take longer (Römer, 1676). It was this discrepancy in Io's orbits over the year that Roemer used as evidence that the speed of light is finite. Though it appeared so, there was no real change to Io's orbit. As Earth is moving towards Jupiter in its orbit around the Sun, light from the star that has reflected off of Io's surface takes less time to travel to Earth and become visible due to Earth meeting the light part of

the way. It takes a shorter period of time for the light to reach Earth, making it appear as if Io's orbit is slightly faster. As Earth is moving away from Jupiter in its orbit around the Sun, light reflected off of Io's surface takes longer to travel towards Earth since the planet is moving away from the moon. It takes a longer period of time for the light to reach Earth, making it appear as if events such as eclipses or transits take longer to occur, and Io's orbit itself is slightly longer.

Roemer calculated that it took 22 minutes for light to travel across the diameter of Earth's orbit, extrapolating from the difference created as Earth moved towards Jupiter on one side of its orbit compared to the opposite side, moving away. In order to prove his calculations to the dubious astronomical community, Roemer accurately predicted that at the end of an eclipse of Io with Jupiter on November 9<sup>th</sup>, 1676, Io would emerge from behind Jupiter 10 minutes later than the previously-believed prediction. His estimate was based off of observations of the moon that Roemer took as the Earth was moving towards Jupiter in August, earlier that year (Römer, 1676). Despite the definitive confirmation of Roemer's experiment, most astronomers continued to believe that the speed of light was infinite and unfathomable, disregarding the late emergence of Io by claiming there could have been interference from the upper atmosphere of Jupiter (Bodanis, 2005). Further into the future, astronomers would accept that the speed of light is a finite value, and the validation of that finitude would be attributed to Ole Roemer.

### **Methods**

This recreation of Ole Roemer's experiment was carried out in two separate ways. The first method used entailed observing 40 revolutions of Io around Jupiter as the Earth was moving towards and away from the planet in the open-source astronomy software Stellarium. The second method used the SeeStar S50 smart telescope to observe Io and Jupiter at the end of the year 2024 and in the spring of 2025. Much like Roemer's original experiment, the aim was not to

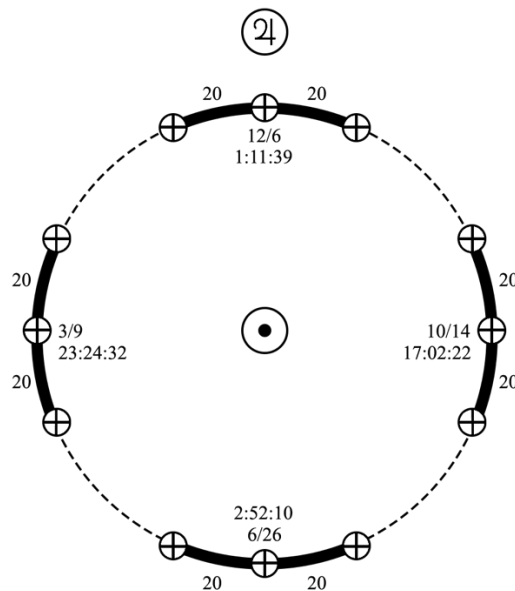
calculate a value for the speed of light, but instead to confirm the discrepancy of Io's orbit that proves the finitude of light's speed.

### Method 1

The exact dates and times in which Earth was and will be closest to, farthest from, and equidistant to Jupiter were found using Stellarium. With each date and time found, 20 revolutions of Io around Jupiter were observed and recorded both before and after the designated point in Earth's orbit around the Sun. This ensured that the 40 observed orbits of Io would be as close as possible – down to the millisecond – to the date and time that Stellarium simulated of the planet-moon system. The diagram found below (Figure 2) was created in order to visualize the orbits of Io observed on any side of the Earth's orbit.

### Figure 2

*Diagram detailing the position of Earth in its orbit around the Sun as it is closest to, farthest from, and equidistant to Jupiter. The 40 revolutions of Io observed are split between each point, labeled as 20 orbits before and after the determined date and time.*



The average period of Io's orbit was determined by calculating the total time it took for 40 revolutions to occur and dividing accordingly. The average orbit of Io as Earth moves towards and away from Jupiter was then compared to when Earth was closest to Jupiter to identify any difference or discrepancy between the orbits of Io.

## **Method 2**

Observations of Io and Jupiter began at the Muriel and Jack Smolen Observatory on SUNY New Paltz campus during the month of December 2024, and continued over the next year during the spring semester in March and April. Each observation session spanned around 2 hours, taking live video-recording in December, and creating a timelapse video in March and April using the SeeStar S50 smart telescope. The first and last frames or exposures for each evening were isolated and compared manually, pixel by pixel, in the image-editing software Adobe Photoshop 2025 once all recordings were acquired. When the distance of Io's orbit was estimated, it was then divided by the video or timelapse length to calculate the apparent velocity of Io. Each apparent velocity was compared between December, March, and April to determine any noticeable difference. In theory, as the Earth is moving towards Jupiter and Io's orbit appears shorter, Io's apparent velocity will increase. As Earth is moving away from Jupiter and Io's orbit appears longer, the moon's apparent velocity will decrease.

## **Results**

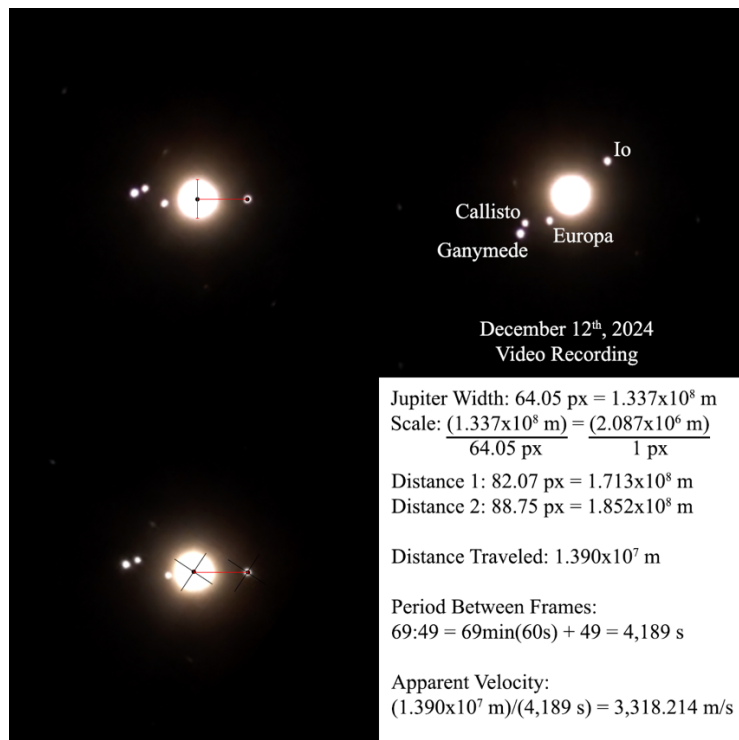
In the first method of this recreation there was a noticeable difference in the calculated periods of Io when compared to the set of revolutions recorded as Earth was closest to Jupiter: the 20 orbits before and after December 6<sup>th</sup> at 1:11:39. As the Earth was moving away from Jupiter, in the orbits of Io before and after March 9<sup>th</sup> at 23:24:32, there was an increase in the average time for Io to complete a revolution by +271.075 seconds per orbit. As the Earth was

moving towards Jupiter, in the orbits of Io before and after October 14<sup>th</sup> at 17:02:22, there was a significant decrease in the average time for Io to complete a revolution by -3,638.150 seconds per orbit.

The second method saw a distinct difference in the apparent velocities of Io during the observations in December compared to those in March and April. Figure 3 shows one example of the calculations made for each observation date and the pixel-to-meter ratio determined using Jupiter's polar diameter in the pixels of the image compared to its actual polar diameter:  $1.337 \times 10^8$  m (Williams, 2024).

### Figure 3

*Compilation of frames and equations taken from the December 12<sup>th</sup>, 2024, recording of Io and Jupiter in order to calculate the apparent velocity.*



For each observation night, the pixel-to-meter ratio was re-calculated based on the changing pixel size of Jupiter's polar diameter. Table 1 describes the apparent velocities

calculated for all recordings taken, significant figures accounted for after the calculations were completed.

**Table 1**

*The apparent velocity calculated for each observation night taken as a part of Method 2.*

<b>Date</b>	<b>Apparent Velocity (m/s)</b>
December 12 <sup>th</sup> , 2024	3,318
December 13 <sup>th</sup> , 2024	390
March 10 <sup>th</sup> , 2025	11,400
March 11 <sup>th</sup> , 2025	8,920
April 9 <sup>th</sup> , 2025	6,300

The average apparent velocity for both the dates in December and March was calculated to more easily compare the change over time, resulting in an average apparent velocity of 1,900 m/s in December, an average apparent velocity of 10,200 m/s in March, and an apparent velocity of 6,300 m/s in April. This did not agree with the theorized scenario in which Io's velocity would appear to slow down as the Earth moved away from Jupiter, instead appearing to speed up.

### **Discussion**

Overall, Ole Roemer's experiment was to determine the finitude of the speed of light and not any exact or numerical values. While this was not achieved by the comparison of apparent velocities in Method 2, the comparison of the average orbit of Io in Method 1 agreed with Roemer's results and analysis. The vast difference between the increase of 271.075 seconds per orbit and the decrease of 3,638.150 seconds per orbit were most likely on account of the time difference between the compared sets of revolutions. The revolutions as the Earth was closest to

Jupiter were taken from 2024, while the compared orbits as the Earth is moving towards Jupiter in October are from 2025. Had the 40 orbits been taken from October 2024, there may have been less of a difference between the two changes in Io's orbit.

There are many improvements that could be made to the recreation of Roemer's experiment should it be repeated in the future, primarily an increase in the number of observed nights for Method 2. This could lead to much more accurate data that can only come from a higher number of trials in any experiment, and may actually provide apparent velocities that appear to slow down as the Earth moves away from Jupiter as Io's orbit should have. Conducting this experiment in warmer weather would also provide ample opportunity to go out on clear nights more often, as most evenings during the data-collecting portion of this experiment were unavailable to take data on account of either a cloudy night or an evening below 20° F. Also in the future, this experiment could be improved by using the 14-inch Celestron EdgeHD telescope mounted in the Smolen Observatory, which was unavailable during this time. This telescope, paired with the ASI2600 MC Air CMOS camera capable of recording video and including metadata in the resulting footage, could vastly improve the accuracy and precision of the data taken.

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