Determining the Speed of Light

Measuring the speed of light has always been a challenge. The reason for the difficulty is that the speed of light is so great that the distances over which we might measure it result in very short time intervals. Only recently has technology enabled us to measure these short time intervals.

In this lesson, we will examine the methods used by various scientists in the quest to determine the speed of light.

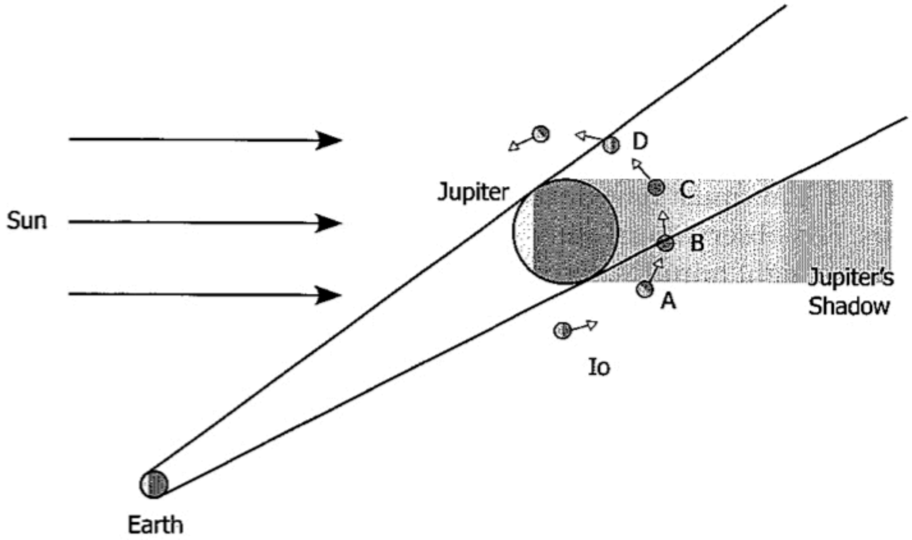
Galileo Galilei (1564–1642)

Galileo attempted to measure the speed of light by measuring the time it took for light to travel a known distance between two hilltops. He and an assistant stood on two hilltops, each holding a covered lantern. Galileo removed the cover from his lantern and started timing. The instant his assistant saw the light from Galileo's lantern, he lifted the cover from his own lantern. As soon as Galileo saw the light from his assistant's lantern, he stopped timing.

Repeated experiments failed to measure any noticeable amount of time for light to travel between the two hilltops. The only conclusion Galileo could make was that the speed of light was extremely fast (he estimated it to be ten times the speed of sound).

Olaus Roemer

Roemer did not initially set out to determine the speed of light. Instead, towards the end of the 16th century, he was studying the eclipses of Jupiter's moon Io. As shown in the diagram below, Io would pass into the shadow of Jupiter at A. At B, Io is totally in the shadow of Jupiter. At C, Io emerges from the shadow, ending the eclipse. At D, Io appears in the line of sight of an observer on Earth, and can be seen once more.



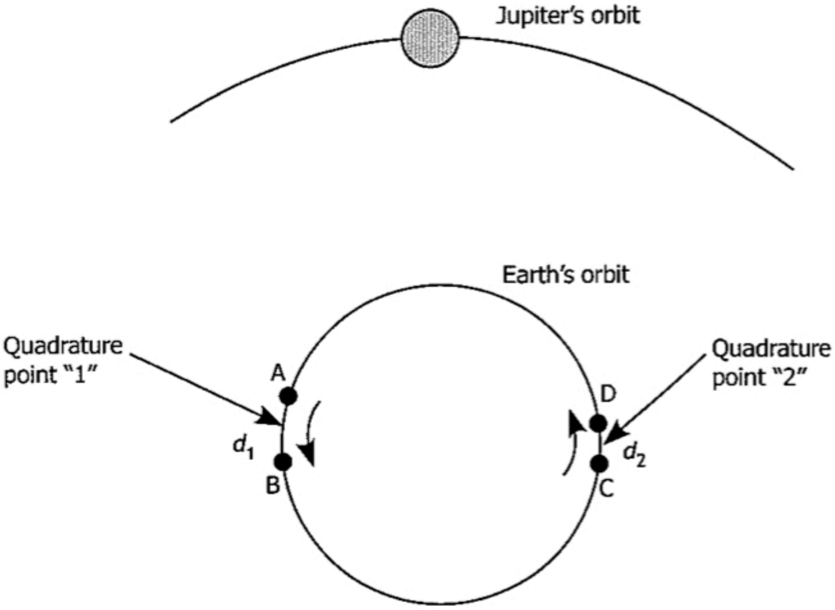
From 1668-1678, Roemer timed eclipses of Io over fifty times. However, not all observations were true eclipses. Occasionally, Roemer was actually timing what is called a **transit**. A transit occurs when the moon Io passes in **front** of Jupiter, rather than behind it.

Some of Roemer's observations were made when Earth was moving towards Jupiter. However, most of his observations were made when Earth was moving away from Jupiter.

From his work, Roemer was able to predict when the next eclipses of Io would occur. Unfortunately, over a period of several months, his predictions were off. He discovered that the eclipses were lasting *longer than expected* whenever Earth was moving away from Jupiter, and *shorter than expected* when Earth was moving toward Jupiter.

Eventually, Roemer was able to determine that the orbital period of Io was slightly longer when Earth was moving away from Jupiter (left side of diagram below) compared to when Earth was moving toward Jupiter (right side of diagram below).

Roemer's Observation



Roemer concluded that the time difference was caused by the difference in the distance between Earth and Jupiter. When Jupiter was closest to Earth, the eclipses happened on time. The farther Jupiter was away from Earth, the later the eclipses became if Earth was moving away. This was because light had a longer distance to travel to Earth.

The size of Earth's orbit and Jupiter's orbit around the sun were known at the time, but only roughly. From this data, Roemer was able to determine the distance from Earth to Jupiter for each of his observations. By dividing the difference in the distances by the difference in the duration of the eclipses, it was possible to determine the speed with which light was traveling.

It is unclear if Roemer actually calculated the speed of light, since most of his notebooks were lost in a fire. It is certain that one of his colleagues – Giovanni Cassini – used Roemer's work to determine that the speed of light was around $2 \times 10^8\ m/s$.

Christiaan Huygens

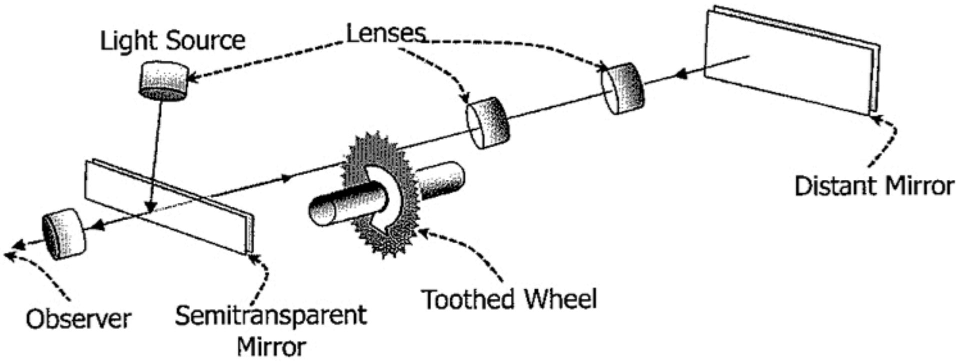
In 1678, Huygens used the size of Earth's orbit, along with the time delay data collected by Roemer, to calculate the speed of light. He was the first to give the speed of light in terrestrial units, expressing it as $16\ 2/3$ Earth diameters per second. This was about two-thirds of the present value for the speed of light, which was not bad work for the time.

Armand Fizeau (1819–1896)

Fizeau shone a light between the teeth of a rapidly rotating toothed wheel. A mirror reflected the beam back through the same gap between the teeth of the wheel. There were over a hundred teeth on the wheel. The wheel rotated at hundreds of rotations per second – therefore, a thousandth of a second was easy to measure.

Light was reflected from mirrors more than six kilometers apart. By varying the speed of the wheel, it was possible to determine at what speed the wheel was spinning too fast for the light to pass through the gap between the teeth and back through the same gap. Fizeau had to decrease the rate of rotation until the first instance at which light was able to pass through the gap going toward the distant mirror, reflect and return through the same gap.

Fizeau's Method for Measuring the Speed of Light

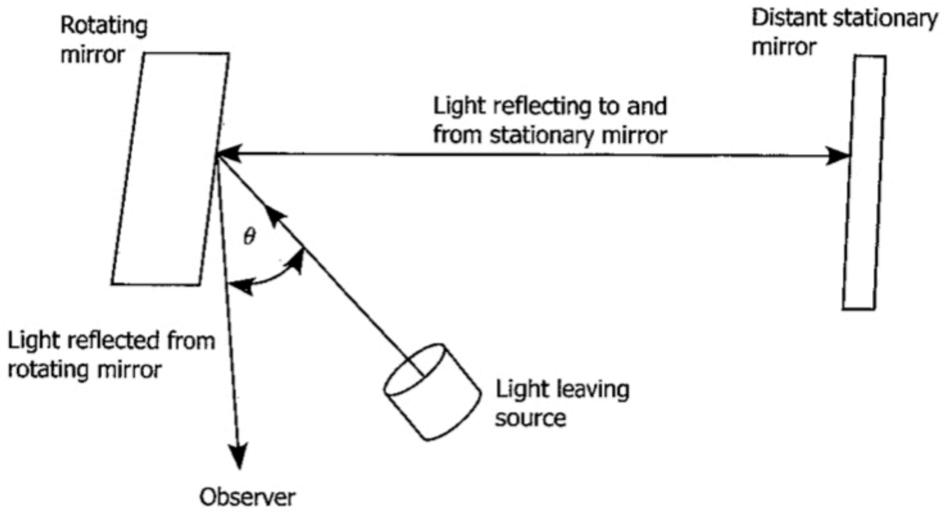


Fizeau calculated the speed of light to be $3.13300 \times 10^8\ m/s$.

Jean Foucault (1819–1868)

Foucault bounced light from a rotating mirror back to a stationary mirror. The light from the rotating mirror bounced back at a slightly different angle than it hit the mirror at – because the mirror was rotating. By measuring this angle, it was possible to determine the speed of light.

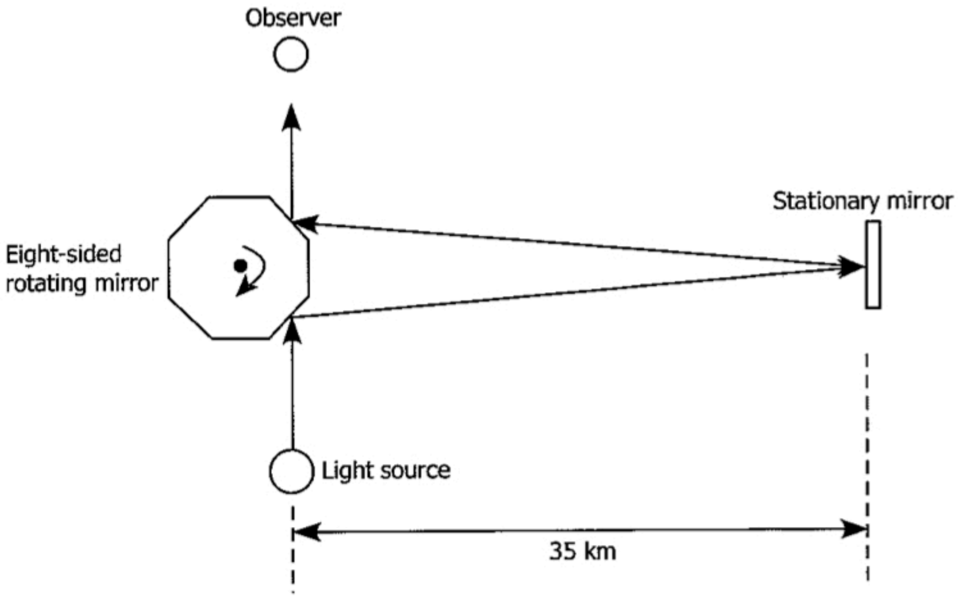
Foucault's Experiment



Foucault continually increased the accuracy of this method. His final measurement determined the speed of light to be $2.99796 \times 10^8\ m/s$.

Albert A. Michelson (1852–1931)

Michelson designed improvements to Foucault's experiment to give much more accurate results. He used a rotating mirror apparatus for a series of high precision experiments carried out from 1880 to the 1920s. Light from a source was directed at one face of a rotating, eight-sided mirror. The reflected light traveled to a stationary mirror and back again, as shown.



The distance between the mirrors was measured to be $35\ 385.5\ m$, accurate to about one part in seven million. This was a much larger distance than the $10\ m$ or so that Foucault used. The rate at which the mirror was rotating was measured accurately using a stroboscopic comparison with an electric signal at standard frequency.

If the rotating mirror was turning at just the right rate, the returning beam of light would reflect from one face of the mirror into a small telescope through which the observer looked. At a different speed of rotation, the beam would be deflected to one side and would not be seen by the observer.

From the required speed of the rotating mirror and the known distance to the stationary mirror, the speed of light could be calculated. Michelson determined the speed of light to be $2.99729 \times 10^8\ m/s$.

Michelson conducted similar experiments using an evacuated tube $1.6\ km$ long to eliminate problems of haze and variations in air density. In these investigations, he determined the speed of light to be $2.99796 \times 10^8\ m/s$.

Today, the accepted value for the speed of light is $2.99792458 \times 10^8\ m/s$.