

From infinite to finite - Measurements on speed of light: A historical review

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Abstract

Light and civilization is synonymous and the search for light's nature and speed was at the center stage of human mind. Galileo first tried to measure the speed of light and from then for the next four hundred years the search continued. In this search the nature of light and its medium of propagation raised many questions. Newton's corpuscular theory or Huygen's wave theory had their own supporters. But everyone was sure about eluding medium named ether to sustain the light. Progress in research shattered the existing belief and gave rise to a new era in the understanding of the universe.

Keywords: Luminiferous ether, corpuscular theory, electromagnetic wave, special relativity, fundamental constant of nature.

1. Introduction

2015 was declared as the 'International year of Light and Light based Technology' by United Nations. Light fascinated human mind from the very beginning of the civilization. Philosophers and thinkers pondered over the nature of light and its speed since ancient time. Harnessing the power of light to use it in various ways was known to many antique civilizations. Early mirrors were made of polished metals. One specimen almost intact, was excavated from the workers' quarter near a pyramid (1900 BC) in the Nile-valley. Parabolic mirrors were used in warfare as burning-glasses to make the ships set ablaze. The famous Greek scholar Aristotle was of the view that light travels with infinite speed. The apparent bending of objects when immersed in water was mentioned by Plato in his well-known book "Republic" [1]. Other Greek philosophers, such as Pythagoras, Democritus, Empedocles, developed several theories about the nature of light. The earliest opinion on the finite speed of light was given by the ancient Greek philosopher Empedocles (490-430 BC), as referred by Aristotle (384-322BC). Aristotle, however, disagreed Empedocles' idea that light must take some time to travel from Sun to Earth [2]. Even Descartes (1596-1650 AD) also believed in Aristotle's idea that light travels instantaneously. Euclid (300 BC), the hero of Alexandria, enunciated the laws of reflection in his book 'Catoptrics' [2]. Rectilinear propagation was a known fact to the ancients. Euclid tried to explain rectilinear propagation as well as law of reflection by stating that light travels via the shortest path between two points. Refraction was studied by Cleomedes (50 AD) and later by Claudius Ptolemy of Alexandria [1, 2]. The remarkable point is that Ptolemy's study was of quantitative nature. He carefully experimented and tabulated the angle of incidence and angle of refraction for the interface of air-water, glass-air and between glass-water. His results are in close agreement with those obtained from Snell's law. Seneca (3 BC to 65 AD) was another prominent Roman philosopher who expressed his thought about light [2]. After the fall of Greco-Roman empire, the centre of scholarship shifted to Arab world. Arabian scholars carefully studied the works of Greek-Roman philosophers and translated them. It was the time when the Caliph of Iraq Abu

Jafr Al-Ma'mun Ibn-Harun set up 'Bait-ul-Hikmat' or the 'House of wisdom' in Baghdad (813 AD) and Muhammad Ibn Musa al-Khwarizmi adopted Arabic numerals from Hindu mathematicians and introduced algebra to the Arabic world (825 AD) [3]. Ibn-Al-Haytham (965-1039 AD) might be called the most influential man from this period whose contribution to optics was of great significance. He suffered from several spree of mental illness and detained from government job. It seems that, during one such period when he was put under house-arrest for 10 years in Cairo, he developed his thoughts on optics and wrote seven volumes of books on optics [4]. Some of his significant comments are about: connection between light and vision, brain is the centre of vision not the eye, rectilinear propagation of light, reflection and refraction, first non-trivial demonstration of 'camera obscura', etc. Al-Haytham's works remained the most significant work in the field of optics till thirteenth century and was translated to Latin. The Latinized version of his name is Alhazen. In the late thirteenth century Roger Bacon (1215-1294) was a prominent name in this field. He first pointed out the possibility of using lenses to correct vision. The new era in optical technology started with the invention of telescope by Hans Lippershey (1587-1619), a Dutch spectacle maker. Within several months Galileo Galilei had made his own version of telescope in Italy. Willebrord Snell, Rene Descartes, Pierre de Fermat, Maria Grimaldi and Robert Hooke had made very important contributions in optics. Hooke proposed the idea that light was a rapid vibratory motion of the medium propagating at a very high speed. This was the beginning of wave theory. And there was Isaac Newton with his corpuscular theory. In the other part of the Europe, a Dutch physicist and mathematician, Christian Huygens, independently working on wave theory, was able to correctly derive the laws of refraction and reflection and explained the double-refraction in calcite, i.e., he discovered the idea of polarization [2].

2. Measuring the speed of light

Thus light was thought a stream of 'corpuscles' by one discipline and as rapid vibration of ethereal matter by other. In any case, everyone was agreed upon the fact that its speed

was exceedingly large. Galileo was the first to question the notion of infinite speed and proposed an experiment to measure the speed of light. The Accademia del Cemento of Florence took Galileo's suggestion and made first attempt to measure the speed of light.

In his experiment, two persons 'A' and 'B' with two covered lanterns went to the tops of two hills one mile apart. First, 'A' uncovered his lantern. As soon as 'B' saw the light, he uncovered his lantern. The time taken by the light to traverse the path from 'A' to 'B' and then 'B' to 'A' was noted. Twice the distance between the hills when divided by this time gave the speed of light. The report on the result of the experiment in 1638 told that no observable delay was found [1]. Actually such crude experiment was not at all fit to measure the enormous speed of light. Its importance lied in the fact that it questioned the age-old notion of infinite speed.

2.1. Ole Roemer and Io

Authentic measurement of speed of light was done by Danish astronomer Ole Roemer at the end of 17th century by his observations on the periodic eclipse of Io, Jupiter's innermost moon. 17th century was a time when almost all countries of European continent were expanding their trade. The importance of navigation increased because of this purpose. The navigators required better maps and specifically an accurate way to determine the longitude. We all know that the difference between times at two places gives the longitude. But the clocks available at that time were not reliable. The scientists at French royal academy of science relied on celestial affair which occur on daily basis after equal interval of time to serve as a reference for both the time at Paris and the time aboard ship. One such event visible everywhere on land or at sea, is the eclipse of the innermost moon of Jupiter, Io, discovered none other by Galileo in 1609. Ole Roemer was engaged in this task along with others. He knew that the period between successive eclipses of Io, varied in the course of year. The maximum time difference between observations taken six months apart, at the same place on earth, was about 22 minutes. This delay was puzzling to the observatory men and all attempts to explain it was not at all convincing. Roemer attributed this delay to the finite speed of light [5]. The time taken by Io to complete a revolution around Jupiter is 42.5 hours. So the moon should enter or leave eclipse behind Jupiter and follow a time table prepared on 42.5 hours interval. But over the year the time lagged further and further behind the predicted timetable. Within six months the earth revolved from a position nearest to Jupiter to farthest from it and the time lag became largest, 22 minutes. During the next six months the time lag reduced gradually, finally became same at the position nearest to Jupiter. Roemer concluded that in six months, the earth reached at a point, diametrically opposite to its previous position. So the extra path traversed, which was equal to the diameter of earth's orbit, by the light coming from Io (actually reflected Sun-light) to reach earth was the reason of this lag. By observing the parallax of Mars in the background of distant stars from two places on earth the distance of Mars from Earth was determined. From this value and the relative distances of all the members of Solar-system known from planetary model, the diameter of earth's orbit was determined to be 182,000,000 miles in those days. So it was traversed in 22 minutes or 1320 seconds according to Roemer's observations. By simple calculation the speed of light came to be 138,000 miles per second.

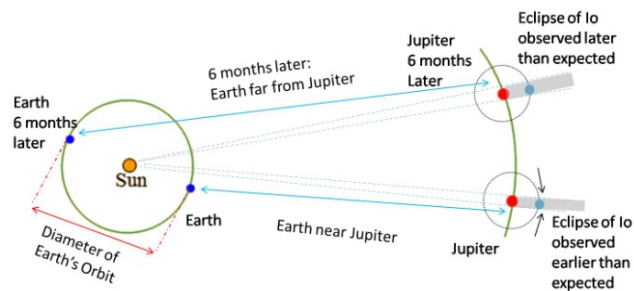


Fig 1: Schematic representation of Roemer's explanation for time-lag of Io's eclipse from calculated schedule.

The importance of Roemer's measurement was that for the first time he calculated the speed which was supposed to be infinite and also the order of magnitude was correct. Today we know that the orbital diameter of earth is 186,000,000 miles and eclipse time lag is not 22 minutes, but 16 minutes and 36 seconds. With these corrections, the same calculation yields the speed as 186,000 miles per second!

2.2. Hippolyte Fizeau: terrestrial measurement

Not everybody was satisfied with Roemer's accomplishment. The main objection was that it depended on astronomical observation and took time to be completed. But the search for terrestrial procedure continued for almost two centuries. In 1849 a wealthy Frenchman, Amanda Hippolyte Fizeau came with a solution [1]. He sent a beam of light from a source to a mirror M₁, which reflected the light to another mirror M₂. The two mirrors are separated by a distance 5.39 miles. Between M₁ and M₂ there was a notched wheel which could be rotated at a regulated speed. The toothed wheel chopped off the light beam into short pulses. When the wheel was at rest, the observer could see the image of the light source through the opening between two adjacent teeth. When the wheel was set in motion and the speed increased, there came a point at which light pulse passing through the opening returned from M₂ just in time for a tooth of the wheel to eclipse it. So the observer saw nothing. When the wheel speed was increased further, the light reappeared and became brighter and brighter until it reached a maximum intensity. The speed of light came to be 194,000 miles per second.

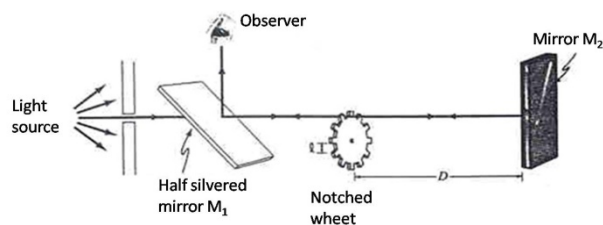


Fig 2: Schematic diagram of Fizeau's experimental setup.

2.3 Further improvement: Jean Foucault and others

Skeptics were many and they made unpleasant remarks about the result. Thirteen years later Jean Foucault tried a somewhat improved version of Fizeau's experiment. The toothed wheel was replaced by a rotating mirror. The rotating mirror turned the returning beam of light at a slight angle. In this arrangement the distance was decreased from more than five miles to 65 feet [1]. Foucault's experiment gave the speed of light in air 185,000 miles per second. He repeated the same experiment with another modification. The light beam was

made to pass through water to measure the speed in water and it came out to be less than that in air. Another ten years later, Marie Alfred Cornu, professor of experimental Physics at Ecole polytechnique in France repeated the notched wheel experiment with some modification and the result came out to be 186,600 miles per second [1].

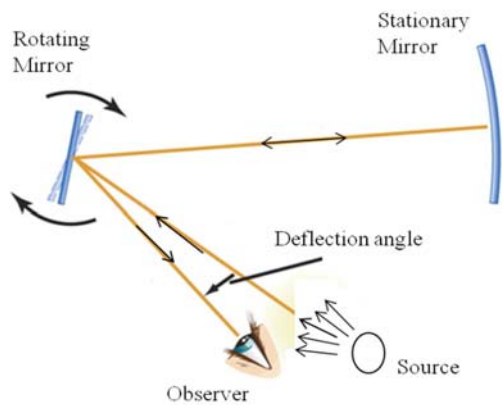


Fig 3: Scheme of Foucault's rotating mirror setup.

2.4. Abraham Albert Michelson: A new figure again

Albert Michelson, an instructor in U.S Navy was challenged by the idea of finding the speed of light with ultimate precision [1]. An interesting event had already happened in 1873 with James Clerk Maxwell published his treatise 'Electricity and Magnetism' [3]. In it he postulated the existence of electromagnetic wave and attributed to it a speed in terms of two fundamental constants of nature, the permittivity and permeability of a medium and that came out to be equal to the speed of light. The question naturally had arisen 'is light an electromagnetic wave?'. Michelson in 1877, made a modification of Foucault's method where he replaced the concave mirror with a plane one and a lens and shifted the rotating mirror from its place. After a series of ten experiments, he came out with a new figure- 186,506 miles per second. It appeared in 1879 in the 'American journal of science'. In 1882 he returned from a sabbatical in Europe and engaged himself in his relentless mission of finding the speed of light. He repeated his experiment for twenty times and came with another figure 299,853km per second, i.e. a little more than 186,000 miles per second. For the coming forty five years it remained the most precise value. After that it was replaced by another one, determined by none other than Michelson himself. In his lifelong pursuit of repeating the tiresome experiment he had no peer. Once Albert Einstein, the stalwart, asked him why he did the experiment and Michelson came with an answer 'because it is such fun' [1].

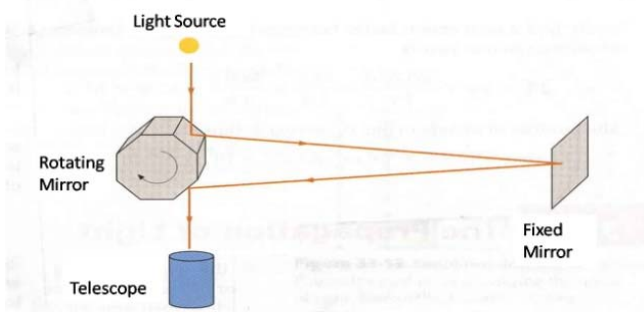


Fig 4: Schematic diagram of Michelson's rotating mirror set up.

2.5. The luminiferous ether: Is it there

During the study tour in Europe, Michelson came across with many great physicists of that time. It was thought in those days that light was propagated through ether, a hypothetical medium having exquisite properties. Sir Isaac Newton, the proponent of corpuscular theory, introduced the concept of 'ether waves' and suggested that both the wave and corpuscular concept were needed to explain the phenomena of light. If one said that there was no ether, it was considered as foolish as saying there was no water in the ocean for the ships to float. Michelson's mind was dragged to this fundamental question and he started thinking about proving or disproving the existence of ether experimentally. Moreover, if ether existed, whether it was stationary or dragged along with the moving body was also a question. Stationary ether was a favoured idea since it provided a frame of reference in space to measure absolute motion. Now, Michelson thought, just like a sailor standing on the deck of a moving ship feels wind blowing across his face, there must be a means to prove the existence of ether wind when earth is rushing in its orbit around the sun through stationary ether.

2.6. Michelson's interferometer: dawn of a new era

The first model of Michelson's interferometer was ready in 1881 AD [1]. He had a very simple thought in his mind. Suppose two boat-men started from the same point on the river. One rowed first down-stream and then upstream to reach the initial point after crossing some distance. The second one rowed across the stream, i.e. perpendicular to the speed of the stream and came back to the initial point after crossing the same distance. Simple vector algebra can show that these two times are different. Michelson in his interferometer did the same thing. He splitted a light beam into two and sent one along a direction and the other perpendicular to it. The two mirrors used in the interferometer were slightly tilted to form a wedge when looking through the observer's telescope; straight fringes could be seen, formed by the interference of two returning beams [6]. In his arrangement it could be possible that one beam travelled across the ether and the other along it. When this apparatus was rotated by an angle 90° , the role of the two beams got interchanged. If there was ether, there should be a shift in fringes [7].

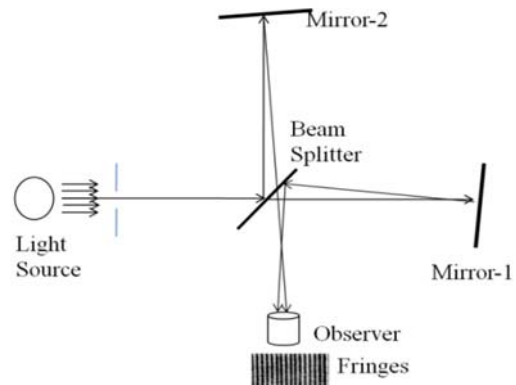


Fig 5: Schematic diagram of Michelson's interferometer set up.

The data were unimaginable. The ether wind, if there was any, had no effect whether the beam travelled along it or across it! He published his results in 'American journal of Science' in 1881AD under the title 'The relative motion of

the Earth and the Luminiferous Ether' and concluded that the hypothesis of stationary ether was wrong. The result invited huge controversy.

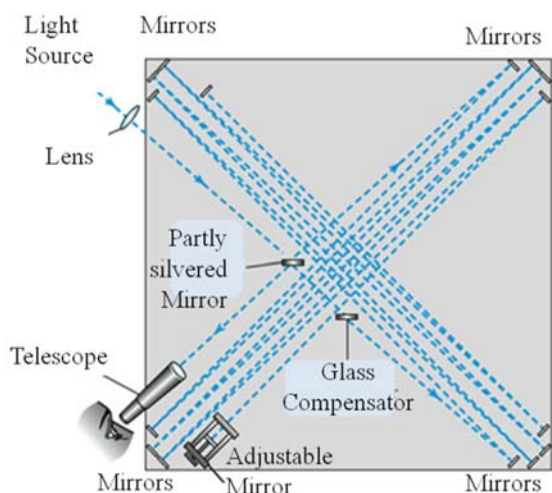


Fig 6: Scheme of Michelson-Morley interferometer set up.

Michelson then collaborated with Morley to repeat the experiment again. The basic principle remained the same but the apparatus had undergone major modification. The light path was increased by repeated reflections by four mirrors. It was so delicately adjusted so that it could measure the tiniest shift in a single wavelength of light. The observation went on during different time of day and night and for different directions. All the collected data were analyzed and again they found that the required shift demanded by the hypothesis of stationary ether was absent [8]. The Michelson –Morley experiment resulted in a shift of current trend in the conception about nature of light and ether. There was a whirlwind of happenings: Lorentz-Fitzgerald contraction hypothesis, discovery of electron by J.J Thompson, Marie and Pierre Curie’s discovery of radioactivity and the spontaneous emission of electrons from radioactive materials with speeds as high as 10,000miles per second and W. Kaufman’s experimental demonstration of change in mass of these absurdly swift electrons; to name a few. Albert Einstein then put forward his revolutionary theory of Special Relativity in 1905 AD and completely changed our notion of space and time [4]. In his theory Einstein said that the velocity of light is constant in free space, the same in all directions and for all observers.

2.7. The search continued

Velocity of light (c) is a fundamental constant of nature and probably the most important of all [9]. It enters into the conversion between electrostatic and electromagnetic units. It relates the mass of a particle to its energy via the celebrated equation $E = mc^2$ and it is used in many relationships connecting other physical constants. Because of its importance, more and more accurate measurements of the speed of light continued. Michelson continued his search until his death in 1931 AD. Other than the terrestrial time of flight method, the technique of the ratio of electrostatic to electromagnetic units gave one of the early accurate measurements of ‘ c ’. The experiment was done by Rosa and Dorsey in 1906 AD and the result came out to be 299,788 kilometer per second [10].

There is another method that can be used in measuring ‘ c ’. We know that the frequency (ν) times the wavelength (λ) gives the velocity of a wave ($\nu\lambda=c$). Essen used a microwave cavity resonator of resonant frequencies 9.5 GHz, 9 GHz and 6 GHz to measure the frequency and wavelength in 1947 and came with a value 299,792 km/sec of c . In 1958 Froome used a moving reflector type microwave interferometer operating at 72 GHz [10, 11]. It was used to measure the microwave wavelength in terms of the length standard. This wavelength, corrected from systematic error and multiplied by the frequency, gave the speed of electromagnetic wave. The new figure was 299,792.5 km/sec.

The most recent measurement used the Methane stabilized helium-neon laser. Its frequency is over 1000 times higher than that of the oscillator used in Froome’s measurement [11]. Direct frequency measurements were extended to this range recently (1983). The wavelength of this stabilized laser has been compared with the krypton-86 length standard [12]. The product of the measured frequency and the wavelength yields a new definitive value for the speed of light which is 299792.458km/sec.

3. Conclusion

Many scientists over the last four centuries spent a lot of time in measuring the speed of light with more and more accuracy. It is a fundamental constant of nature. Einstein’s theory of special relativity, which revolutionized the concept of space and time and bid adieu to Galilean relativity, based on the postulate that speed of light is invariant in all reference frames. Electrostatic to electromagnetic unit conversion includes the speed of light. The mass energy conversion which is crucial in subatomic particle domain requires the speed of light. The standard of length is redefined. A small error in ‘ c ’ may cause an enormous error in the measurement of distance of stars and galaxies. And needless to say that with every new technique, the saga of human intellect and endeavour continues.

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