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A STUDY ON MEASUREMENT OF SPEED OF LIGHT

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ABSTRACT

Starting from ancient Greeks who believed that light travels at infinite speed, scientists and astronomers performed lots of experiments to answer the "million dollar question" - finding the speed of light. This study is a compilation of some of the path breaking experiments carried out by eminent scientists to calculate the speed of light. These experiments laid a new foundation to the field of physics.

Keyword: - *Interferometry, Aberration, Cavity resonance, Electromagnetic radiation and Toothed gearing.*

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1. INTRODUCTION

Initially the experiments were astronomical done by Ole Roemer and James Bradley. Then in the 19th century it went through a mechanical transformation-using rotating mirrors and wheels which were done by Fizeau, Foucalt and Michelson. In the mid- 20th century electromagnetic experiments peeked in. Cavity resonance and inferometry experiments determined the speed of light to great accuracy.

In 1983 the metre was defined as "the length of the path travelled by light in vacuum during a time interval of 1⁄299792458 of a second",fixing the value of the speed of light at 299792458 m/s by definition, as described below. To reach that point of accuracy, many experiments were conducted using Astronomical, Mechanical and Electromagnetic methods.

2. MEASUREMENT OF SPEED OF LIGHT BY ASTRONOMICAL MEASUREMENTS

2.1 Eclipse of Io by Jupiter

Ole Christensen Rømer used an astronomical measurement to make the first quantitative estimate of the speed of light. When measured from Earth, the periods of moons orbiting a distant planet are shorter when the Earth is approaching the planet than when the Earth is receding from it. The distance travelled by light from the planet (or its moon) to Earth is shorter when the Earth is at the point in its orbit that is closest to its planet than when the Earth is at the farthest point in its orbit, the difference in distance being the diameter of the Earth's orbit around the Sun. The observed change in the moon's orbital period is caused by the difference in the time it takes light to traverse the shorter or longer distance. Rømer observed this effect for Jupiter's innermost moon Io and found that light takes 22 minutes to cross the diameter of the Earth's orbit. He concluded that the speed is about 220000km/s.

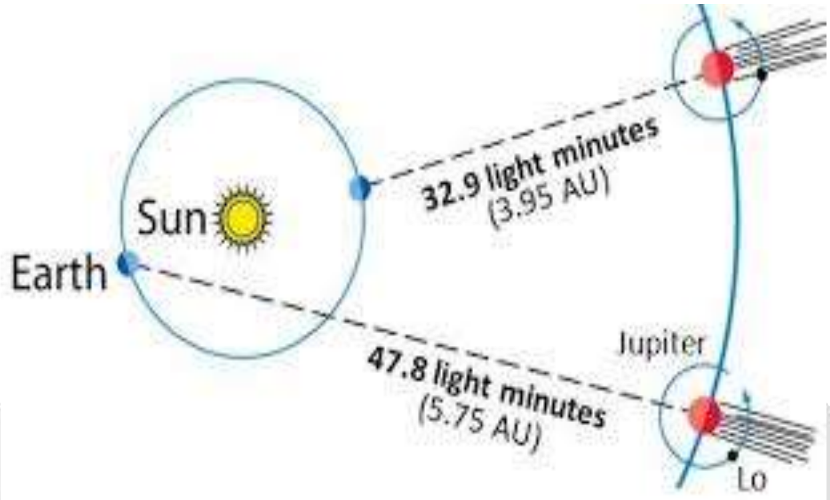

Fig -1: Measuring speed of using moons of Jupiter

2.2 Aberration of light

Another method is to use the aberration of light, discovered and explained by James Bradley in the 18th century. This effect results from the vector addition of the velocity of light arriving from a distant source (such as a star) and the velocity of its observer (see diagram). A moving observer thus sees the light coming from a slightly different direction and consequently sees the source at a position shifted from its original position.

A star emits a light ray which hits the objective of a telescope moving to the right. While the light travels down the telescope to its eyepiece, the telescope moves to the right. For the light to stay inside the telescope, the telescope must be tilted to the right, causing the distant source to appear at a different location to the right. Light from a distant source appears to be from a different location for a moving telescope due to the finite speed of light.

Since the direction of the Earth's velocity changes continuously as the Earth orbits the Sun, this effect causes the apparent position of stars to move around. From the angular difference in the position of stars (maximally 20.5 arcseconds) it is possible to express the speed of light in terms of the Earth's velocity around the Sun, which with the known length of a year can be converted to the time needed to travel from the Sun to the Earth. In 1729, Bradley used this method to derive that light travelled 10210 times faster than the Earth in its orbit.

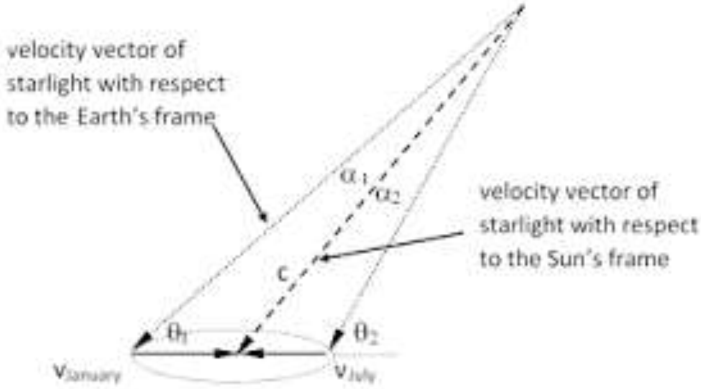

Fig -2: Measuring the speed of light using aberration of light

3. MEASUREMENT OF SPEED OF LIGHT BY MECHANICAL EXPERIMENTS

3.1 Fizeau method

Light from a source *S* passes through a convex lens LI. The transmitted beam is intercepted by a semi-transparent inclined glass plate *G*. A part of the light is reflected and is converged near the rim of a toothed wheel W which can be set into rapid rotation. The light passing through the space between two consecutive teeth is made parallel by a convex lens **L2.** This parallel beam travels for 8.6 km and is then converged by a convex lens **L3.** A plane mirror *M* is placed in the focal plane of the lens **L3.** The reflected light is again made parallel by the lens **L3** and it converges at the rim of the wheel. If it finds a gap, it falls on the glass plate *G*. The beam is partially transmitted and an observer receives these rays to see the image of *S* through a telescope.

When the wheel is rotated, it allows light to pass through in separate bursts. Light is passed when a gap comes at *F* and is stopped when a tooth comes there. The speed of rotation of the wheel is gradually increased while the observer keeps looking for the image. Initially, the image flickers but at a particular angular speed the image cannot be seen at all. This happens when the angular speed is such that by the time light passes through a gap, goes to the mirror *M* and comes back, the next tooth comes at *F*. Any light passing through the wheel does not return to the observer and the image cannot be seen. The angular speed of the wheel is carefully measured in this state. Suppose,

D = distance from the wheel W to the mirror *M*,

ω = angular speed of rotation of the wheel when the image is completely unseen for the first time,

n = number of teeth in the wheel.

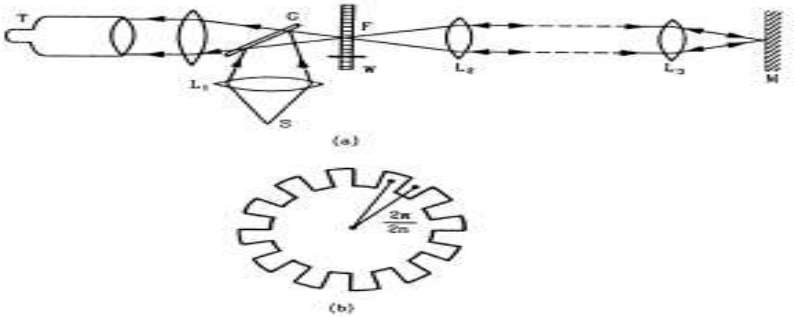

Fig -3: Measuring speed of light in Fizeau method

The speed of light c is given as $C = 2Dn\omega/\pi$

Difficulties: Since the light has to travel a large distance, the intensity decreases considerably and the final image becomes very dim. Secondly, the experiment cannot be done inside a laboratory. It needs an open space of several kilometers.

3.2 Foucalt method:

The basic principle of Foucault's method can be understood with the help of figure below. Light from a source *S* is partly transmitted by a glass plate *G* and is incident on a convex lens *L*. The distance of the lens from *S is* so adjusted that the beam transmitted through the lens is convergent. This beam is intercepted by a plane mirror M1 which can be rotated about an axis perpendicular to the plane of the figure.

The plane mirror reflects the light which converges on a concave mirror **M2.** The distance between the two mirrors is equal to the radius of curvature of the concave mirror. The concave mirror reflects the light beam back to the plane mirror. The central ray is always incident on the concave mirror perpendicularly so that it retraces the path. If the plane mirror does not rotate, the rays retrace the path up to the *glass* plate *G.* A part of the beam is reflected by the *glass* plate and forms an image *I* of the source. Now, suppose the plane mirror M1 rotates by an angle A0 by the time light goes from M1 to **M2** and comes back to it. The light reflected by M1 then makes an angle 200 with the direction of the rays reflected earlier. Because of this deviation, the returning rays (shown dotted in figure 21.2) form an image *I'* of the source which is slightly shifted from the position *I.*

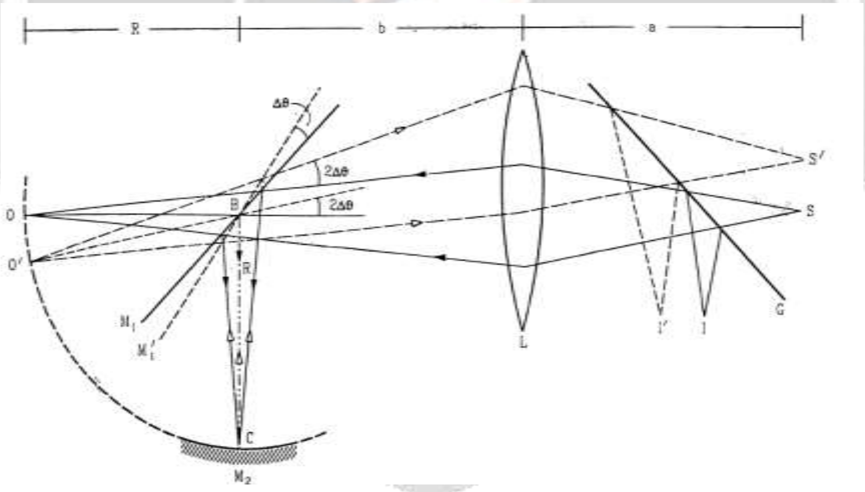

Fig -4: Foucalt method for measuring speed of light

Let,

R = radius of the concave mirror,

ω = the angular speed of the plane mirror,

s = the shift *II'*,

b = the distance from *M,* to *L,*

a = the distance from *L* to *S.*

When the mirror is in position MI, the rays reflected by it to the lens seem to come from a point O which is the image of the point *C* in M1. When it has rotated by an angle AO, the rays reflected by it to the lens seem to come from a point 0' which is the image of *C* in the new position M'1 of the mirror. The distance $BO = BC = R$. It is clear from the figure that $00' = R(\Delta\theta)$.

Now, the rays reflected by the position M1 of the mirror retrace the path and would converge at the source *S* itself. The glass plate partly reflects the beam to converge it at *I.* Thus, *I* is the image of *S* in the plate *G* acting as a plane mirror. Similarly, the rays reflected by the position M'1 of the mirror are converged by the lens at a point *S'.* The glass plate *G* partly reflects the beam to converge it at I' which is

the image of *S'* in *G.* It is clear that

$SS' = s$.

Thus, the lens *L* forms an image of 0 at *S* and of 0' at *S'.* If we place an object of size 00' at *0,* its image will have the size *SS'* at *S.* Thus,

Magnification=SS'/OO'=image distance/object distance= $a/((R+b))$

The variation in θ is $\Delta\theta = \omega\Delta t = 2R\omega/C\Delta$.

From the above equations, speed of light is: $C = (4R^2\omega a)/(s(a+b))$

Foucault obtained a value 2.98 x 10^ 8 m/s from his measurement.

3.3 Michelson method:

The scheme of Michelson method to measure the speed of light is shown in the figure. Light from an intense source *S* is incident upon one face of a polygon shaped Mirror *M.* The light reflected from this surface is sent to the lower portion of a concave mirror **M3** after reflections from two plane mirrors M1 and **M2.** The geometry is set so dial the light reflected from the concave mirror becomes parallel. This parallel beam of light is allowed to travel through a long distance (several kilometers) and falls on the lower portion of another concave mirror **M4.** The parallel beam is converged at the focus of *M4* -where a plane mirror **M5** is placed. **M5** reflects the beam back to the concave mirror **M4,** this time at the upper portion. As **M5 is** at the focus, the beam reflected by **M4** becomes parallel and travels back to the concave mirror **M3.** After proper reflections from **M3** and the plane mirrors, it is sent to the polygonal mirror. A telescope is adjusted to receive the rays reflected by the polygonal mirror and hence, to form an image of the source. Suppose the polygonal mirror *M* is stationary. Light from the source falls on the face ab of the mirror *M* and after reflections from all the mirrors, finally falls on the face *ef* of the mirror *M.* The image of *S* is seen in the telescope. If the polygonal mirror rotates, the face *ef* also turns a little while light travels between the two reflections from the polygonal mirror. The light thus fails to enter into the telescope and the image is not seen. If the rotational speed of the mirror is gradually increased, a stage comes when the adjacent face *fg* takes the place of *ef* by the time light comes there. Then, the light is again sent into the telescope. In the experiment, one looks through the telescope and gradually increases the angular speed of the polygonal mirror. The image flickers initially and becomes steady at a particular angular speed of the mirror. This angular speed is measured.

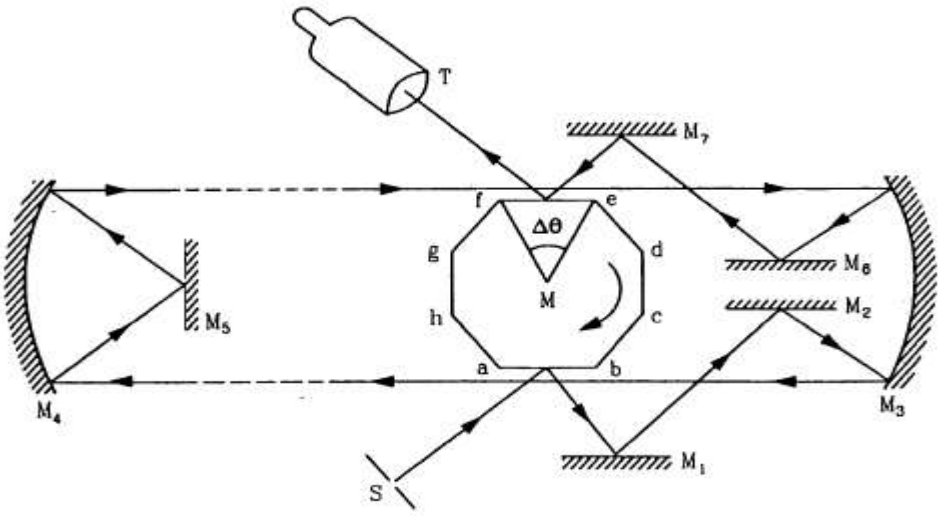

Fig -5: Michelson method for determining speed of light

Suppose,
N = the number of faces in the polygonal mirror,
ω= the angular speed of rotation of the mirror when the image becomes steady,
D = the distance travelled by the light between the reflections from the polygonal mirror.

If the speed of light is c, the time taken by the light to travel the distance D *is* $\Delta t = D/c$. The angle rotated by the mirror during this time is $\Delta\theta = 2n/N$.
The angular speed of the mirror is $\omega = 2\pi C/DN$.
So, the speed of light is given by, $C = \omega DN/(2\pi)$

3.4 Time of flight techniques

One of the last and most accurate time of flight measurements, Michelson, Pease and Pearson's 1930–35 experiment used a rotating mirror of 32-faces and a one-mile (1.6 km) long vacuum chamber which the light beam traversed 10 times. It achieved accuracy of ±11 km/s.

A light ray passes horizontally through a half-mirror and a rotating cog wheel, is reflected back by a mirror, passes through the cog wheel, and is reflected by the half-mirror into a monocular.

4. MEASUREMENT OF SPEED OF LIGHT BY ELECTROMAGNETIC EXPERIMENTS

4.1 Cavity resonance

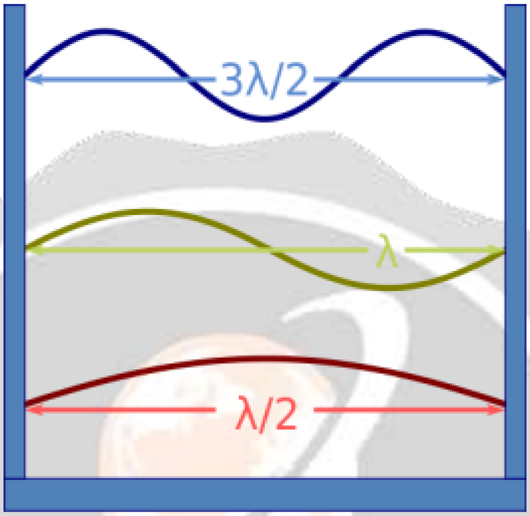

Fig -6: A box with three standing waves

Like standing sound waves in a pipe, similarly, electromagnetic waves undergo resonance in a cavity. Using dimensions of the resonance cavity wavelength of the wave can be determined. Using the value for the frequency of the wave, using the formula c=fʎ, where c is the speed of light, ʎ is the value of the measured wavelength of the wave and f is the frequency of the wave.

In 1946, Louis Essen and A.C. Gordon-Smith established the frequency for a variety of normal modes of microwaves of a microwave cavity of precisely known dimensions. The dimensions were established to an accuracy of about ±0.8 μm using gauges calibrated by interferometry. As the wavelength of the modes was known from the geometry of the cavity and from electromagnetic theory, knowledge of the associated frequencies enabled a calculation of the speed of light.The Essen–Gordon-Smith result, 299792±9 km/s, was substantially more precise than those found by optical techniques. By 1950, repeated measurements by Essen established a result of 299792.5±3.0 km/s.

4.2 Interferometry

Interferometry is another method to find the wavelength of electromagnetic radiation for determining the speed of light. A coherent beam of light from a laser, with a known frequency (f), is split to follow two paths and then recombined. By adjusting the path length while observing the interference pattern and carefully measuring the change in path length, the wavelength of the light (λ) can be determined. The speed of light is then calculated using the equation $c = \lambda f$.

In 1972, using the laser interferometer method and the new definitions, a group at the US National Bureau of Standards in Boulder, Colorado determined the speed of light in vacuum to be c = 299792456.2±1.1 m/s.

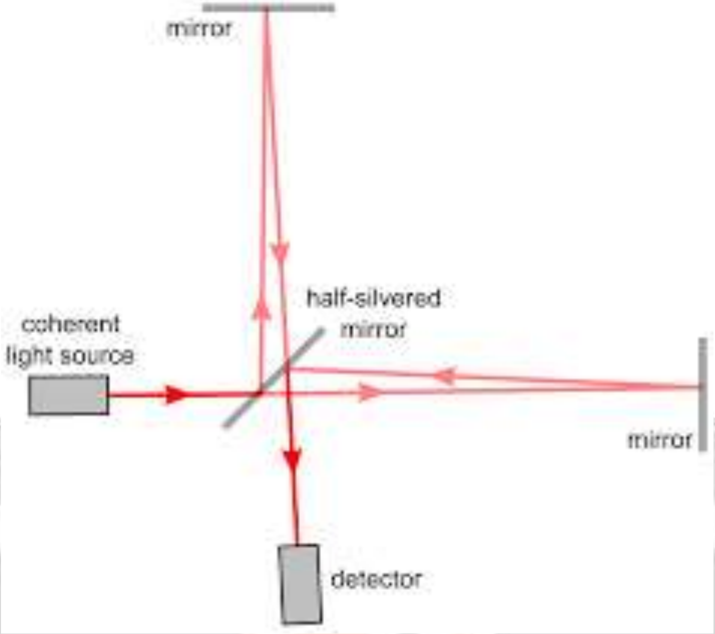

Fig -7: Measuring speed of light using Interferometry

Table -1: Comparison of different experiments

YEAR	PERSON	METHOD	MEASURED VALUE	ERROR
1675	Ole Romer and Huygens	Moons of Jupiter	220000 km/s	-27%
1729	James Bradley	Aberration of light	301000 km/s	+0.40%
1849	Fizeau	Toothed wheel	315000 km/s	+5.1%
1862	Foucalt	Rotating mirror	298000 ± 500 km/s	-0.60%
1926	Michelson	Rotating mirror	299796 ± 4 km/s	+12 ppm
1950	Essen and Gordon- Smith	Cavity resonator	299792 ± 3.0 km/s	+0.14 ppm
1972	Evenson	Laser interferometry	299792.4562 ±0.0011 km/s	-0.006 ppm
1983	17th CGPM	Definition of the metre	299792.458	Exact

5. CONCLUSION

With improvements in technologies, the experiments have gained more impact in accuracy factors. Moreover worldwide developments in almost all fields of science have also credited to this fact. Finally it was decided by the CGPM to keep the speed of light is 299792458 m/s as exact value and define the fundamental unit of length using it.

6. REFERENCES

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