Speed of Light in Historical Perspective

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Three pivotal empirical measurements determined the speed of light in relation to a moving observer or its source.

1. Ole Roemer (1644–1710) found that the speed of light from Jupiter's satellite was lower when an observer on earth was moving away from it, and higher on approach.
2. James Bradley (1693–1762) determined that the speed of light from a star was higher when an observer on earth moved towards its perpendicular incident, and lower on recession.
3. Albert Michelson (1852–1931) examined the speed of light when both the source and the observer were on the same moving earth. Under these circumstances the speed surprisingly did not change. The experiment was interpreted to mean that the speed of light was not affected by the motion of the earth. However, the results published in the 1881 paper were then amended in a second paper from 1887. In this paper the speed in the perpendicular direction was increased, in the spirit of Bradley's aberration, and this correction diminished the expected discrepancy by half. The speed in direction of the earth's motion, in the spirit of Roemer's data, was however not similarly considered.

All the above data indicated that the speed of light was affected by the speed of the frame of reference.

1. Introduction

Speed is measured in reference to a certain frame, such as the speed v of a train in reference to the stationary earth. The speed of a person moving inside this moving train c in reference to the same earth is than added to that of the train when the motion is in the same direction $v+c$ or subtracted when in the opposite direction $v-c$. These laws of motion were first published in the 13th century by Nicole Oresme, and are usually termed motions in 'Inertial Frame of Reference', 'Galilean Frame of Reference' or 'The Principle of Relativity' [1].

George Francis FitzGerald (1851–1901) [2-3] and Hendrik Antoon Lorentz [4-6] interpreted the ether drift experiments of Albert A. Michelson [7-8] to mean that the speed of light was always the same whether the frame of reference was stationary or was moving. It was a universal constant. The empirical data available at the end of the nineteenth century are examined in the following article in an attempt to verify whether or not they supported the conclusions derived from them.

2. Roemer's Measurements

Roemer actually discovered two facts. First, he found that the *point in time* of Io's eclipses (the beginning or end of the period) as measured from earth when it was nearest Io (point H, Fig. 1) occurred earlier on the clock than when the earth was farthest away (point E). The difference was about 22 minutes; therefore, Roemer concluded, light must have a certain velocity V, for it took time T to cover the distance D of the diameter of the earth's orbit around the sun ($V=D/T$).

The second fact Roemer found was that the *duration* of Io's periods was longer when earth was in the process of receding from Jupiter (from L to K), and shorter when earth was on the approach (from F to G), than when it was at a fairly constant distance from the light source (at H or E). This second measurement is hardly ever mentioned in the relevant literature and may have been forgotten. The difference between one period measured from a fairly stationary position compared to the same period measured from a receding or approaching position was quite small, but became obvious when Roemer added forty periods on approach, compared to forty periods measured at rest, or compared to forty periods on recession. As recorded in the *Philosophical transactions* of 1677 [9]:

> "For, as M. Roemer had examin'd the thing more nearly, he found, that what was not sensible in two revolutions, became very considerable in many taken together, and that, for example, forty revolutions observed at the side F, might be sensibly shorter ["plus courtes" in the original French] than forty others observed in any place of the Zodiack where Jupiter may be met with."

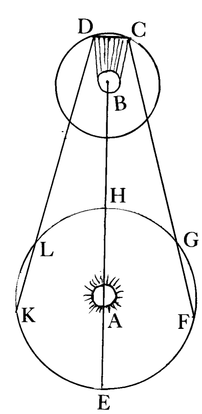

Fig. 1. Roemer's analysis

Furthermore, the loss of time on approach equaled the gain on recession, and the mean of the two equaled the period measured from a stationary position. Roemer's data concerning light thus appear perfectly in accord with data derived from the general treatment of motion—the motion of anything at all. Again, Roemer discovered basically *two* things: (1). The *begin and end* of the period occurred at a later time when measured at point E (Fig. 1), a long *distance* from Jupiter, than when measured at H a shorter *distance* from the planet. [2]. At equidistance from Jupiter, the *length* of the period was greater when the *direction* of the earth was away from the planet from point L to K, and shortest of all when the earth's *direction* was towards Jupiter at position F.

Ernst Mach [10] compared the revolutions of the satellite to the revolving sails of a windmill; their light is *slower* to reach a receding observer and their revolutions therefore appear longer; the opposite occurs on approach as the speed of light in reference to the observer increases and the wings appear to rotate faster.

In order to make Roemer's ideas quite clear, let us think of the revolving sails of a wind-mill. At a constant distance from an observer the revolution of the sails appear to be just as quick as it actually is. If, however, the observer moves away very quickly, the revolution must appear slower, because the light from each successive position reaches him later. The period of revolution apparently depends upon the *relative velocity* [emphasis added] with regards to the observer. The principle thus expressed differs from the well-known Doppler principle only in its application.

The mill's wings may be substituted with the hands of a clock: on recession they *seem* to move slower, time *seems* to passes slower, and on approach time seems faster, unless you know your speed and the speed of light, and add or subtract their speeds according to classical kinetics principles. If instead you imagine the speed of light to be unrelated to the speed of its source or observer, you must conclude that either distances shrunk or your time dilated.

Instead of being stationary at L, a distance D from D, take the observer to be moving away from D at a uniform speed v while the light signal is leaving D. By the time the signal which left D at time 0°° reaches position L, L itself has moved farther; the question is at what time will the observer receive the signal? We designate with d the unknown distance from L which he covers until he receives the signal at K. The time elapsed since leaving L until the reception is d/v, which equals the time it takes the signal to arrive from D, $d/v = (D+d)/c$. By transposition we obtain:

$$dc = (D+d)v = Dv + dv \tag{1}$$

$$Dv = d(c-v) \quad => \quad D/(c-v) = d/v\,. \tag{2}$$

Now look at the value of d/v we started with, and obtain

$$(D+d)/c = D/(c-v)\,, \tag{3}$$

which means that the time it takes to cover the distance to reception at K when K is stationary equals the time it takes to receive the signal at a receding position L with the signal moving at the lower speed of $c-v$, or, in reference to an observer receding at speed v from a signal of speed c the speed of the signal is lower than when he was stationary. The signal that left D at 0°° o'clock will reach L later, and the time period between signals will be longer. The opposite occurs when the observer approaches Jupiter, namely the periods shorten.

3. Bradley's Observation

In the early part of the 18th century a controversy was alive as to whether the fixed stars exhibited a parallax observable from earth. James Bradley (1693-1762) and his rich friend Samuel Molyneux set out to investigate the problem in the latter's home in Kew by London. They aimed a telescope at a bright star in the constellation Dragon, *gamma draconis*, which in that latitude was almost straight overhead - thus to avoid atmospheric refraction and aid accurate positioning of the telescope relative to a plumb line. As Bradley reported to the Royal Society in 1728, these observations revealed that all stars overhead seemed to move in direction of the earth's motion around the sun, and during the course of one year completed a full circle whose diameter subtended about 40″ [11, 12].

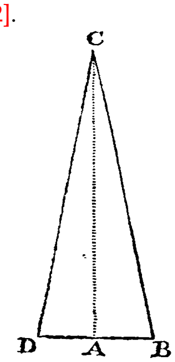

Fig. 2. Bradley's original diagram

When the earth in its annual orbit went from B to A (Fig. 2, form Bradley's original paper) Bradley had to change the direction of his telescope from straight upwards (AC) to a little forwards (BC) in order to see the star overhead (C), and when orbiting the other way the tilt of the telescope was reversed at the same angle.

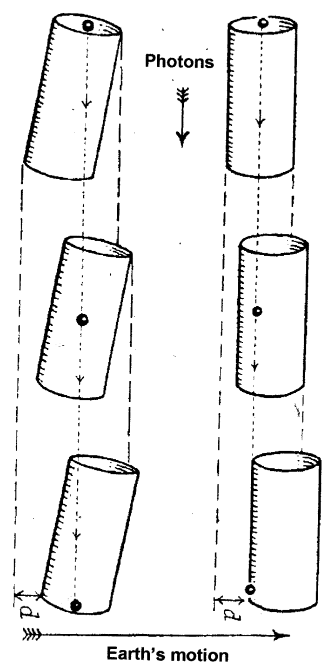

Fig. 3. Caption

Having pondered the phenomenon for some time, Bradley concluded that the angular *aberration* in the position of the star was an effect caused by the compounding of the motion of the observer on earth moving at speed v in one direction [B to A] (in reference to the fairly stationary extraterrestrial firmament) with the motion of the light at speed c [C to A] moving almost perpendicular to this observer. The value of the earth's velocity and the angle of aberration being known, Bradley deduced the velocity of light ($c = v/\tan\alpha$), and his result concurred very well with the then only available other data obtained by Roemer's method.

The fact of aberration means that the speed of light c' (C to B) referred to a moving earth ($\sqrt{c^2 + v^2}$ or $c/\cos\alpha$) is greater than the speed of light referred to a stationary earth (C to A). As the speed of light varied with the speed of the observer in Roemer's measurements so it did in Bradley's. Accordingly, so far, it seems that the speed of light follows the general principles of all motions as established by Galileo and Newton.

Later, in the nineteenth century, the phenomenon of aberration stuck as a thorn in the body of Huygens' and Dr. Young's prevailing wave theory, perhaps due also to the language of Bradley's original report of its discovery in 1728, using Newton's term "Particles of Light". The complete faith in the actual existence of a material, ethereal ether was then the firm basis for interpreting optical phenomena, and was perhaps the prime cause of the ensuing problems.

4. Michelson's Experiment

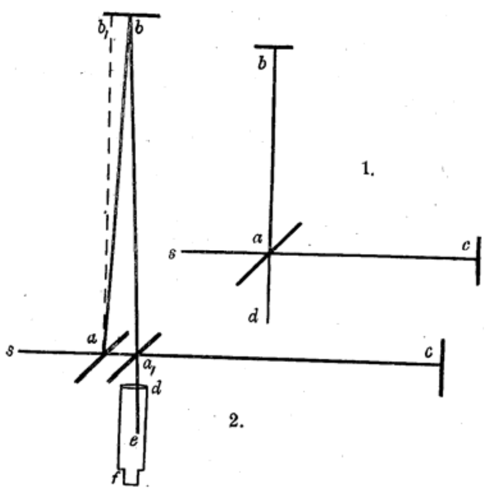

Fig. 4. Michelson's apparatus

Michelson had a very sensitive instrument constructed by Schmidt and Haensch in Berlin, where he resided at the time. Basically the apparatus (Figure 4, right) consisted of two equally long arms with mirrors (*b,c*) at one end of each. Light from the flame of a small lantern (*s*) was split in two by a plane-parallel plate (*a*) and the recombined beams, reflected from the mirrors, were observed (*d*). The returned beams, refracted by the plate and reflected by the mirrors, formed fringes, bands of brighter and darker light. If the speeds of going forward with the earth's direction were different when the whole apparatus was rotated perpendicular to the earth's motion, then these fringes would shift, be in a different position. Light was first transmitted when arm *ac* was in direction of the earth's motion around the sun while arm de was perpendicular to it, and then the instrument was rotated at a right angle and the observation repeated. Michelson wrote: "Let

V = the velocity of light.

v = the speed of the earth with respect to the ether.

D = the distance between the two points.

d = the distance through which the earth moves, while light travels from one point to the other.

d_1 = the distance earth moves, while light passes in the opposite direction.

"Suppose the direction of the line joining the two points to coincide with the direction of earth's motion, and let

T = time required for light to pass from the one point to the other,

T_1 = time required for it to pass in the opposite direction,

T_0 = time required to perform the journey if the earth were at rest."

Now let's examine the definitions carefully. Let V be the velocity of light in reference to what? As Michelson himself often measured it [and received the Nobel for this work], it was always the speed between two *stationary* positions on earth.

And here was the crux of the problem: "D" is the distance between two points on earth. "d" is the distance the earth moves in reference to what? Michelson said, "Assuming then that the ether is at rest, the earth moving through it". To what point of reference was the ether at rest? It was always taken that the earth moved in reference to some other generally accepted stationary object or medium outside it, such as the stars or the sun. The decisive difficulty was that Michelson was not observing the phenomena from a stationary position outside the earth or outside the ether. On the earth itself, without an external point of reference, the distance "d" cannot be determined.

Now, therefore, if the earth moved in reference to an external stationary medium or object, the velocity of light traveling in the same direction on this earth, as employed by Michelson in his experiment and as seen from the stationary position in outer space, would necessarily be $V + v$, not simply v. No evidence whatsoever existed in Michelson's time to permit neglect of compounding the velocity of light with the velocity of the source or observer; on the contrary, Roemer and Bradley had already furnished the necessary data in support of the fact.

Furthermore, if "T = the time required for light to pass from one point to the other" [on the moving earth equals D/V], and light's velocity in reference to a stationary position outside earth increased by the earth's velocity, then it should be:

$$T = (D + d)/(V + v), \tag{4}$$

But instead Michelson wrote

$$\text{“}\ T = (D + d)/V\ \text{”}. \tag{5}$$

The velocity of light V was *a priori* not compounded by the velocity v of the source on the earth moving in reference to the stationary ether or sun, while the distance covered $D + d$ was indeed reckoned in this frame. *The events were considered confusedly from two different points of reference and therefore could not possibly correspond.*

In 1881 he said: "If, however, the light had traveled in a direction at right angles to the earth's motion it would be entirely unaffected, and the time of going and returning would be, therefore, $2D/V = 2T_0$." [T_0 = time passed when the earth is assumed to be at rest]. He did not explain why it was entirely unaffected.

However, in the 1887 paper he admitted:

"In deducing the formula for the quantity to be measured, the effect of the motion of the earth through the ether on the path of the ray at right angles to this motion was overlooked… It may be mentioned here that the error was pointed out to the author of the former paper by M. A. Potier, of Paris, in the winter of 1881."

Compared to the diagram of 1881, (and Figure 4, right) the perpendicular ray in 1887 did not go perpendicularly to b_1 but a bit forward to position b (Figure 4, left). "The angle bab_1 being equal to the aberration α … Let it now be required to find the difference in the two paths aba_1 and aca_1."

The angle of aberration in Bradley's case was formed by a moving observer on earth in reference to the stationary source, the star. When Michelson's case is viewed from a stationary point outside earth, the angle was formed by the moving light source in reference to this stationary observer, which as we know since Oresme and Copernicus, is the same thing. The compounding of the velocity of light by the velocity of the observer created the angle of aberration in both observations, and the value *ab* in Michelson's case was certainly larger than ab_1, just as Bradley's velocity CB was higher than CA. Whatever force moved the light from position b_1 to *b* in the experiment was imparted to it by the motion of the earth, the same motion that moved the observer Bradley from position B to A. Had the light from the source not been compounded by the earth's motion (momentum) it would have gone perpendicularly to b_1, and thus missed the mirror which was already a little forward.

Michelson then accepted the fact that the motion of the earth altered (increased) the motion of light in the perpendicular direction: "In consequence, the quantity to be measured had in fact but one-half the value supposed."

When in 1887 it was admitted in this manner that the earth's motion influenced the distance and speed of light in its perpendicular direction, it may seem no small oversight not to have gone back and corrected the 1881 calculations for the forward direction as well. And yet the definitions have not changed: "Let V = velocity of light", that is, the light emanating from the source on the moving earth. Now if the velocity of the transverse ray was compounded by the earth's motion, it must do so also in direction of its forward motion, and velocity V was in reality $V + v$ (as pointed out previously). When incorporating this correction into the calculations the other "one-half of the value supposed" is found, and the two opposing rays do indeed cancel one another, and the null shift in fringes comes as no surprise or disappointment.

As we well know since Oresme, Galileo, and Newton, inside a space moving uniformly forward, such as a train or the earth, all linear motions and speeds are the same as when the space was stationary.

5. Conclusion

The idea propounded at the end of the nineteenth century that the speed of light in moving inertial frames of reference was constant was not evidently supported by the then available empirical data.

Acknowledgements

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