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The "delay-time" model: A simple derivation of the new formula for the speed of light through a moving optical medium

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Abstract

Within the framework of the "delay-time" model, outlined by us in a previous paper [1], a new formula for the speed of light through a moving optical medium was derived. In the paper mentioned above, that formula was derived using an equivalence concerning the total time in which light travels the length l of a tube, at rest in the laboratory reference system, through which an optical medium moves with the velocity $\vec{v}$. In the present paper a more detailed presentation of the "delay-time" model was made, and the new formula for the speed of light through a moving optical medium was derived in a simple way, based on a reasonable approximation regarding the length of the optical path traveled by light when propagating over a distance L in the laboratory reference system, through an optical medium moving with the speed $\vec{v}$ relative to it.

Keywords: Speed of Light, Moving Optical Medium, Delay Time, A New Formula, Optical Path.

1. Introduction

In 1810, at the urging of Simone Laplace, Francois Arago conducted an experiment to verify the dependence of the speed of light coming from various stars on the massiveness of those stars and their relative velocities with respect to the Earth [2]. The null result of Arago's experiment could not be explained within the corpuscular theory of light and Arago asked Jean Augustine Fresnel to explain it within the wave theory of light.

The wave theory of light was revived in the early 19th century with the discovery of the phenomenon of light interference by the English scientist Thomas Young [3]. In his theory regarding the wave nature of light, Thomas Young postulated that, in order to propagate through a vacuum, light needed a material medium, which he called luminiferous ether. To explain the very high value of the speed of light and the phenomenon of light aberration highlighted by the English astronomer James Bradley [4], the luminiferous ether had to fill the entire Universe, be immobile and have a low density but an extremely high elasticity.

In 1818, in a letter to Arago, Fresnel explained the null result of Arago's experiment in terms of a new model of ether, named the model of the partially entrained ether [5]. According to this model, the speed of light propagation through an optical medium, having the refractive index n in its proper reference system and moving with the speed $\vec{v}$ relative to it, is:

$$c' = \frac{c}{n} + v(1 - \frac{1}{n^2}) = \frac{c}{n} + f \cdot v \tag{1}$$

Relation (1) was called Fresnel's formula for the speed of light through a moving optical medium and the factor f was called Fresnel's ether dragging coefficient.

In 1851, The French scientist Hippolyte Fizeau decided to experimentally verify the correctness of Fresnel's partially entrained ether model [6]. The method used by Fizeau was a differential one, based on measuring the interferential effects generated by the appearance of very small differences in the optical paths traveled by two coherent light beams, which travel the same geometric path in opposite directions, through the same optical medium, at rest or moving with speed $\vec{v}$ relative to reference system of the place where the measurements are made, which we will hereinafter call the laboratory reference system (LRS).

Fizeau's experimental device contained a U-shaped tube through which water or air was either at rest or flowing at a certain velocity $\vec{v}$. With the help of a system of beam splitters, mirrors and lenses, the light coming from the Sun was divided into two coherent beams, which propagated through the water in the tube, one parallel to the speed $\vec{v}$ of the water, and the other antiparallel to it (Figure 1).

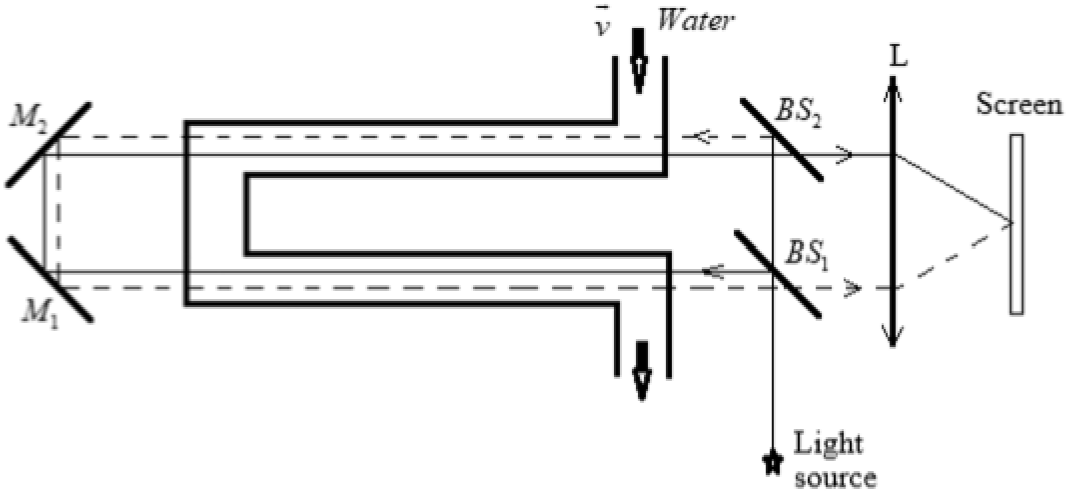


Figure 1. A sketch of Fizeau's experimental device.

The measurements made by Fizeau consisted of determining the band width, (β), that is the distance between two consecutive fringes, and measuring the displacement of the interference pattern, Δx, when water flows through the tube, with respect to its initial position, when the water was at rest in the tube.

Fizeau expressed the result of his experiment by a relative quantity, called the fringe shift (FS), defined by the relationship:

$$(FS) = \frac{\Delta x}{\beta} \tag{2}$$

Since $\beta = \frac{\Delta x \cdot \lambda}{c \cdot \Delta t}$, (FS) can also be expressed by the relation:

$$(FS) = \frac{c \cdot \Delta t}{\lambda} \tag{3}$$

The average value of the fringe shifts measured by Fizeau, was:

$$(FS)_{\text{exp}} = 0.23016 \tag{4}$$

In his paper [6], Fizeau compared the experimental results with the theoretical predictions offered by the three hypotheses regarding the ether, existing at the time of his experiment:

- Stokes's hypothesis, of fully entrained ether: $(FS)_{Stokes} = 0.4597$
- Young's hypothesis, of the non-entrained ether: $(FS)_{young} = 0$
- Fresnel's hypothesis, of the partially entrained ether: $(FS)_{Fresnel} = 0.2022$

Fizeau's conclusion was that "*the third hypothesis put forward by Fresnel, leads to a displacement value very close to the observational result*".

The null result of the Airy experiment of 1871 [7], predicted by Fresnel over 50 years earlier, strengthened the conviction of scientists of the time that Fresnel's formula could adequately explain optical phenomena.

However, many scientists of the time expressed their lack of confidence in the dubious and assumption-based way in which Fresnel arrived at his formula. In this context, in a paper published in 1872 [8], Mascart even asked theorists to look for other theoretical explanations for Fresnel's formula <u>or for a slightly different one</u>.

An important moment in the evolution of ideas regarding the luminiferous ether was the emergence of Maxwell's theory of electromagnetism [9]. Shortly after the emergence of this theory, in 1892, Lorentz proposed replacing the mechanical ether of Young, Fresnel and Stokes with an electromagnetic ether, weightless and totally immobile, whose only property remained that of allowing the propagation of electromagnetic waves [10]. However, this ether model could not adequately explain the null result of the Michelson-Morley experiment of 1887 [11] and Lorentz had to abandon it.

The luminiferous ether, this ghostly medium, which appeared in physics solely from Young's desire to provide light with a material support necessary for its propagation through space, received a devastating blow in 1905, with the appearance of Albert Einstein's paper "The electrodynamics of the moving bodies" [12]. In his paper, Einstein showed that, since none of the experiments carried out up to that point had been able to detect the movement of the material bodies relative to ether, the use of the luminiferous ether in explaining optical and electrodynamic phenomena was unnecessary and therefore must be eliminated.

In addition, according to the Theory of Relativity, Fresnel's formula can be derived by applying the relativistic velocity composition rule and neglecting the higher order terms of the v/c ratio:

$$c' = \frac{c/n + v}{1 + \frac{c/n \cdot v}{c^2}} = \frac{c/n + v}{1 + v/cn} \cong (c/n + v)(1 - v/cn) \cong \frac{c}{n} + v(1 - \frac{1}{n^2}) \qquad (5)$$

After 1905, the hypotheses based on the existence of the ether, as a supporting medium for the propagation of light and as an absolute reference system, gradually disappeared from physics. However, there are still scientists who believe that many of the problems of modern physics can be better explained by continuing to appeal to the ether.

One of the recent physical models based on the existence of the ether is the "time-delay" model of the Italian scientists Giuseppe Antoni and Umberto Bartocci [13]. According to this model, the ether is neither stationary nor totally or partially dragged by bodies moving through it, but simply it is the one that drives the Earth into motion (Descartes-Leibniz vortex theory).

This assumption causes the Earth to be permanently at rest in the ether reference system, and the speed of light, relative to the Earth, to be permanently c, regardless of the state of motion of the light source relative to the Earth. Obviously, the above-mentioned assumption is equivalent, in effect, to Einstein's principle of the constancy of the speed of light.

In addition, the two Italians stated that, in the case of the Fizeau experiment, it can be considered that "*the ether is not dragged at all by the moving water, and that the only physical phenomenon we are dealing with in this case is that the light, during its travel through the moving water (say for a time* Δt*) simple meets fewer obstacles, and that the single delay for each obstacle is (for instance in the case of water moving in the same direction as the light) less than (3)*" .

Based on these assumptions, Antoni and Bartocci finally arrived at an expression for the speed of light through a moving optical medium identical to Fresnel's formula.

2. The “delay-time” model.

The "delay time" model was developed starting from the "time-delay" model of the Italian scientists Giuseppe Antoni and Umberto Bartocci.

Unlike the "time-delay" model, the "delay-time" model does not take into account the existence of the luminiferous ether and admits the validity of the second postulate of the Theory of Relativity, according to which the light emitted by a light source, at rest or in uniform motion with respect to the laboratory reference system, propagates with a speed c relative to it.

Also, within the "delay-time" model, it is considered that the appearance of a delay time during the propagation of light over a distance L through an optical medium, at rest or in motion relative to the laboratory reference system, occurs as a result of an interaction, at a microscopic level, between the photons of the light beams and the particles of that optical medium.

The difficulty of clearly establishing the physical phenomena involved in the interaction of a photon with the particles of the medium through which it propagates, forced us, in this first stage, to resort to a macroscopic method of determining the speed of light through a moving optical medium.

As in the "time-delay" model, within the "delay-time" model it is assumed that the change in the speed of light when propagating through a moving optical medium, compared to its speed through the same optical medium at rest with respect to the laboratory reference system, is mainly due to the change in the number of particles of the medium overcome by light per unit length.

3. A simple derivation of the new formula for the speed of light through a moving optical medium

We consider a tube of length L, at rest in the laboratory reference system, through which an optical medium (water) circulates with constant velocity $\vec{v}$, relative to it. The refractive index of the optical medium, measured when it is at rest in the laboratory reference system, is n.

We also consider that a beam of monochromatic light, coming from a light source, at rest or in motion with respect to the laboratory reference system, propagates through the water in the tube in the direction of its velocity, $\vec{v}$.

In the time interval Δt_+, in which the light travels the length L of the tube, the water travels the distance $v \cdot \Delta t_+$ that the light will no longer travel, because the water column of length $v \cdot \Delta t_+$ leaves the tube (see Figure 2).

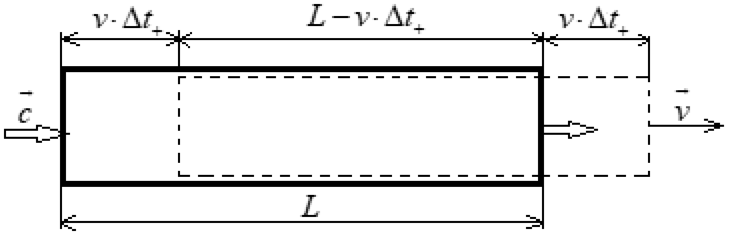


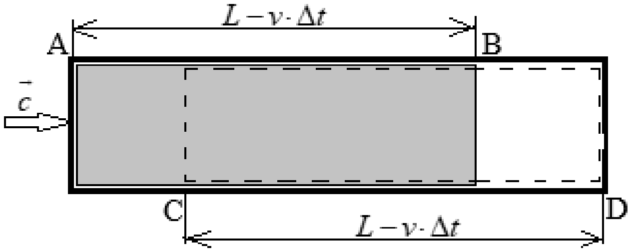
Figure 2.

It follows that, from the entrance to the tube to the exit from it, the light crosses a column of water of length $L - v \cdot \Delta t_+$.

The length of the optical path traveled by light in the time interval Δt_+ can be determined, with a very good approximation, using an equivalence similar to that used by us in [1], but this time in a more explicit way.

We first consider that a column of water, of length $L - v \cdot \Delta t_+$, is at rest relative to the tube, in position AB (see Figure 3).

Figure 3.



The length of the optical path traveled by light when crossing the tube of length L is, in this case:

$$(\Delta x_1)=(L-v\cdot\Delta t_+)n+v\cdot\Delta t_+ \qquad (6)$$

But, in the time interval Δt_+, the water column moves from position AB to position CD.

As a result of this, the length of the optical path traveled by light through the tube decreases with $v\cdot\Delta t_+\cdot n$ and increases with $v\cdot\Delta t_+$.

It follows that the total length of the optical path traveled by light through the tube of length L, is:

$$(\Delta x)=(L-v\cdot\Delta t_+)n+v\cdot\Delta t_+-v\cdot\Delta t_+\cdot n+v\cdot\Delta t_+=Ln-2v\Delta t_+(n-1) \qquad (7)$$

But, the length of the optical path traveled by light in the time interval Δt_+ can also be expressed by the relationship:

$$(\Delta x)=c\cdot\Delta t_+ \qquad (8)$$

So:

$$c\cdot\Delta t_+=Ln-2v\cdot\Delta t_+(n-1) \qquad (9)$$

Finally, it results that, the speed of light relative to the laboratory reference system when it propagates through an optical medium in the direction of its speed, $\vec{v}$, relative to the laboratory reference system, has the expression:

$$c_+=\frac{L}{\Delta t_+}=\frac{c}{n}+2v(1-\frac{1}{n}) \qquad (10)$$

If light propagates through the optical medium in the tube in the opposite direction to its speed $\vec{v}$, in the Eq. (10) the sign of the speed v will be reversed, and the speed of light relative to the laboratory reference system will have the expression:

$$c_-=\frac{L}{\Delta t_-}=\frac{c}{n}-2v(1-\frac{1}{n}) \qquad (11)$$

An analysis of Eq. (10) would indicate the existence of a new coefficient of light entrainment by moving optical media:

$$f' = 2(1 - 1/n) \tag{12}$$

In reality, there is no entrainment of light by moving optical media, and the increase in the speed of light is determined, in this case, mainly by the decrease in the number of particles of the medium that the light overcomes per unit length.

A more thorough analysis of Eq. (10) and another method of determining it, based on a new hypothesis regarding the propagation of light through optical bodies, will be done in a future paper.

In what follows, we will compare the theoretical prediction for the fringe shift, determined within the “delay-time” model, with the results of the Fizeau experiment.

In Fizeau's experiment, the total length of the U-shaped tube was 2L. The difference between the time intervals in which the two light beams travel through the U-shaped tube of the Fizeau device is:

$$\Delta t = \Delta t_{-} - \Delta t_{+} = \frac{2L}{c_{-}} - \frac{2L}{c_{+}} = \frac{2L}{\frac{c}{n} - 2v(1-\frac{1}{n})} - \frac{2L}{\frac{c}{n} + 2v(1-\frac{1}{n})} = \frac{8Lv(1-1/n)}{\frac{c^2}{n^2} - 4v^2(1-\frac{1}{n})^2}$$

Neglecting the term $v^2(1-1/n)^2$, we obtain:

$$\Delta t = \frac{8Lvn(n-1)}{c^2} \tag{13}$$

By introducing Eq. (13) into Eq. (3), we obtain the expression of the theoretical prediction for the fringe shift, according to the “delay-time” model:

$$(FS)_{delay} = \frac{8Lvn(n-1)}{\lambda \cdot c} \tag{14}$$

The values of the physical quantities used in the Fizeau experiment were:

$v = 7.059 m/s$ (average speed of water through the tube)

$L = 1.487 m$ (length of a branch of the tube)

$n = 1.33$ (refractive index of water)

$\lambda = 526 \cdot 10^{-9} m$ (wavelength of light in vacuum).

By using these values in Eq. (14), we obtain:

$$(FS)_{delay} = 0.2335 \tag{15}$$

It is observed that the theoretical prediction determined according to the "delay-time" model is very close to the average value of the interference fringe displacements measured by Fizeau

$((FS)_{\exp} = 0.23016)$. In the Eq. (14) the velocity v represents the average velocity of the water through the tube, which can be experimentally determined with high precision.

Fizeau-type experiments were designed so that light propagated through the center of the tubes. Although aware that the flow of water through the tubes of Fizeau-type experiments is a turbulent flow, for which the radial distribution of water velocities is unknown, many scientists, including Fizeau himself, considered that the velocity of the water through the center of the tube should be greater than the average velocity of the water through the tube. In this context, in their 1886 experiment [14], Michelson and Morley estimated that, in the case of turbulent water flow through a cylindrical tube, the speed of water through the center of the tube $(v_{\max})$, should be 1.165 times greater than its average speed through the tube:

$$v_{\max} = 1.165 \cdot v \tag{16}$$

But the experimental method used by Michelson and Morley in estimating the correction factor of 1.165 was mechanically invasive, and therefore, in our opinion, unreliable.

If in Eq (14) the average velocity v is replaced by $v_{\max}$, the “delay-time” model prediction deviates from the value experimentally determined by Fizeau by about 18%, becoming:

$$(FS)_{delay} = 0.272 \tag{17}$$

At the same time, the prediction based on Fresnel's formula comes very close to the result of the Fizeau experiment:

$$(FS)_{Fresnel} = 0.2355 \tag{18}$$

4. Conclusion

The Fizeau experiment demonstrated that the speed of light through an optical medium is influenced by the movement of that medium relative to the laboratory frame of reference in a different way than that indicated by Newtonian mechanics.

The results of Fizeau's experiment were interpreted satisfactorily using Fresnel's formula, derived by him at the beginning of the 19th century, within the framework of the partially entrained ether model. Subsequently, Fresnel's formula was derived in many other theoretical models, both classical and relativistic.

Due to its success in explaining the results of a large number of famous experiments (Arago, Fizeau, Hoek, Airy), Fresnel’s formula has become the most widely accepted formula expressing the speed of light through a moving optical medium. But, despite the empirical success of the Fresnel’s formula, many of the physical models within which it was derived are open to criticism.

The “delay-time” model, outlined by us in a previous paper [1] and completed in the present paper, emerged as a result of our belief that a theory based on the interaction between light and the particles of the medium through which it propagates would better explain the results of the Fizeau experiment. In our opinion the "delay-time" model, represents only a step towards a new phenomenological theory, which will explain in detail the propagation of light through an optical medium.

Within the delay-time model, a new formula for the speed of light through a moving optical medium was derived. The derivation of the new formula was based on an approximation, in our opinion quite reasonable, regarding the length of the optical path traveled by light when propagating over a distance L, in the laboratory reference system, through an optical medium moving with a speed $\vec{v}$ relative to it.

The theoretical prediction of the fringe shift obtained by using this formula coincides almost perfectly with the average value of the fringe shift experimentally determined by Fizeau, if in the formula expressing this prediction the velocity v is the average velocity of the water through the tube.

If the average velocity is replaced by the maximum velocity of the water through the tube, estimated by Michelson and Morley to be 1.165 times its average velocity, the theoretical prediction of the "delay-time" model deviates by about 18% from the experimental result, while the prediction given using Fresnel's formula coincides almost perfectly with it.

Taking into account the above statements, it is clear that the "delay-time" model would correctly describe the propagation of light through a moving optical medium, only if the speed of water through the center of the tube of a Fizeau-type device would have a value very close to the value of the average speed of water through the tube. This would be possible because in Fizeau-type experiments the flow of water through the tube is totally turbulent (Re>10000) and, in this case, the profile of the radial velocities of the water through the tube could not be precisely determined.

Establishing clearly, through mechanically non-invasive experiments, the relationship between the average velocity of water through a tube and its velocity through the center of the tube, would make the Fizeau experiment a truly *experimentum crucis*, capable of distinguishing between the various theoretical models concerning the propagation of light through moving optical media.

This would implicitly lead to obtaining more reliable information about light.

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