PRECISION MEASUREMENT OF THE ONE-WAY SPEED OF LIGHT AND IMPLICATIONS TO THE THEORY OF MOTION AND RELATIVITY

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Introduction

The speed of light, without doubt, is the most discussed and the most important aspect in theories of motion and relativity. Its large value, relative to speeds familiar or practically imaginable in daily life, implies that some of the relativistic effects are too small and subtle to be noticed except in specialized experiments, whereas certain other effects, like the energy released in conversion of matter to energy, are larger than one could possibly imagine from experience. Its fundamental essential role in the theory of relativity, and the special relativistic assertion that the speed of light is a universal constant independent of the speed of the source or of the observer are familiar and well known. People often say that if there is one thing that is absolute in the theory of relativity, it is the speed of light. It is this assumption that allows special relativity to assert that an observer in inertial motion in empty space is completely equivalent to an observer at rest.

In this backdrop, it will be surprising, and perhaps shocking to some, to note that the constancy of the speed of light relative to a moving observer is not an experimentally established fact[1]. What is experimentally well established is the fact that the two-way speed of light that is measured in a reference frame is independent of the speed of the frame, and that the results are identical to a measurement performed in a frame at rest. To understand the fundamental difference between this measurement and the one in which the one-way speed of light is to be measured, we need to first discuss certain aspects of the propagation of waves in a medium and of the measurement of the velocity of propagation. We will also discuss a novel technique for the measurement and comparison of the one-way speed of light. This will be followed by a brief review of the relevant experiments, which will establish that the one-way speed has never been measured directly before. Then we will present the result from a recent experiment that shows that the speed of light relative to an observer depends on the velocity of the observer in exactly the same way the speed of other familiar waves. These results will clearly establish the logical and operational circularity that was present in the special theory of relativity regarding the speed of light relative to moving observers. Also, the experimental results support strongly the prediction of first order anisotropy of the one-way speed of light in the theory of cosmic relativity[2] based on the gravitational influence of the matter filled universe on entities moving through the preferred frame of the isotropic universe[3].

Conceptual and mathematical aspects

Consider an experiment to measure the speed of a wave-train. One needs to fix a standard distance (for the time being we will assume that this is known, though for the measurement of the speed of light this aspect has to be defined correctly, as we will do later). Figure 1 indicates the scheme.

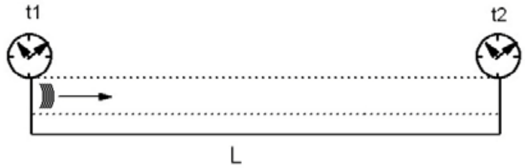

Figure 1: Two clocks are required in a conventional one-way speed measurement.

Clearly, the measurement of one-way speed requires two clocks that are pre-synchronized. Again, for familiar measurements (speed of water waves for example) the synchronization is not a problem. The one-way speed will be given by the expression

$$v_o = L/(t2 - t1) \tag{1}$$

The measurement can also be done using just one clock if the wave-train is reflected back at the end of the track such that it reaches back to the starting point. This avoids the need to synchronize two clocks; only one stable clock is required, since a clock is synchronous with itself. Then the two-way speed is given by

$$v_{tw} = 2L/(t1' - t1) \tag{2}$$

The difference between the two measurements become apparent when we consider the situation where the entire measurement scheme of the frame of reference including the clocks, start and finish points etc. move relative to the medium in which the wave-train is moving. See figure 2.

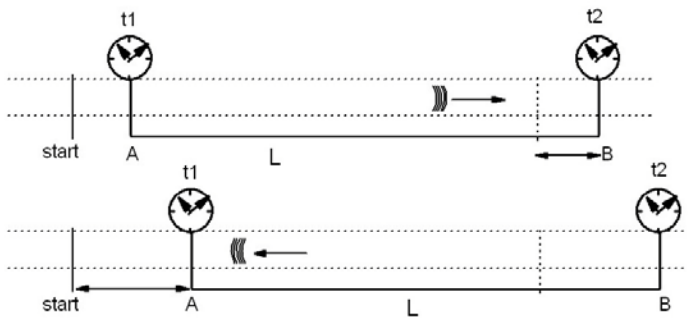

Figure 2: Diagram to explain the important conceptual and physical difference between the measurements of the one-way speed and the two-way speed.

The upper panel explains the situation when the reference frame is moving to the right as the wave-train is propagating at its natural speed *c* relative to the medium. Since the reference point B moves away, the waves have to catch up a further distance before they reach B where the clock is, and it takes more time to cover the distance L as judged by the observer in the moving frame. During the time *t* taken by the wave-train to reach from point A to B, the point B would move out by the distance *vt*. Therefore the effective one-way speed v_o' is smaller.

$$\begin{aligned} v_o t &= L + vt \\ v_o' &\equiv \frac{L}{t} = v_o - v \end{aligned} \tag{3}$$

We see that the speed of the waves in the medium is independent of the speed of the source, but it is dependent on the speed of the observer. This is the general situation regarding all known waves in situations where the wave-speed is determined by the properties of a preferred frame or medium. Now consider the lower panel of figure 2. Here the wave is reflected back at B and it moves towards A, retracing its earlier trajectory. In this two-way propagation, the point A moves to the right by a distance *vT* and catches up with the waves during the time *T* the waves takes to complete the two-way propagation. The total time taken for the two-way trip is

$$T = \frac{L}{v_o - v} + \frac{L}{v_o + v} = \frac{2L}{v_o^2(1 - v^2/v_o^2)} \tag{4}$$

Therefore, the effective two-way speed of the waves relative to the moving observer is

$$v_{tw} \equiv \frac{2L}{T} = v_o\left(1 - v^2/v_o^2\right) \tag{5}$$

It is this modified velocity dependent two-way speed that Michelson and Morley sought to compare with the two-way speed in a direction perpendicular to the motion of the reference frame. What is important to note is that the two-way speed has no first order dependence on the velocity of the observer's frame whereas the one-way speed does have such dependence.

If one wants to avoid using any clock at all in such measurements, then a comparison of speeds in two different directions may be done, and this is what Michelson and Morley attempted. For example the effective two-way speed in a perpendicular direction is

$$v_{tw}^{\perp} = v_o\sqrt{1 - v^2 / v_o^2} \quad (6)$$

and interestingly the one-way speed in this direction is identical. Therefore, when one compares the two speeds by forming an interferometer, the experiment is sensitive to only the ratio of the two velocities and that is given by

$$\frac{v_{tw}}{v_{tw}^{\perp}} = \sqrt{1 - v^2 / v_o^2} \quad (7)$$

Therefore, the Lorentz-Fitzgerald hypothesis that the arm of the interferometer that is parallel to the velocity of the frame contracts by the factor $\sqrt{1 - v^2 / v_o^2}$ explains the null result in the M-M experiment. Since these details are well known, we will focus on the fact that such a cancellation does not happen if one is dealing with the one-way speed of light. Then the ratio is

$$\frac{v_{tw}}{v_{tw}^{\perp}} = \frac{v_o(1 - v / v_o)}{v_o\sqrt{1 - v^2 / v_o^2}} \simeq 1 - v / v_o \quad (8)$$

There is a first order correction. But such a measurement is not possible, as we will see later. What is however possible is a comparison of the one-way speeds in exactly opposite directions, one parallel to the velocity of the observer and another anti-parallel. Then also the ratio and the difference of the two one-way speeds depend on the velocity of the observer to first order in v / v_o. In fact, if we could measure the one-way speed of light in the parallel and antiparallel direction over a length *L,* the difference in time taken by the two wave-trains is expected (from our analysis so far) to be

$$\delta T = \frac{L}{c - v} - \frac{L}{c + v} = \frac{2Lv}{c^2(1 - v^2 / c^2)} \quad (9)$$

without considering second order effects like length contraction. (We have now written the speed of the waves with symbol *c,* to conform to standard usage.) Even if those effects are considered, the first order term does not change. Note the crucial difference between a one-way comparison and a two-way comparison. It is clear from this discussion that the dependence of the speed of light on the velocity of the observer, if any, cannot be studied using measurements that use a two-way propagation technique when there are physical effects like length contraction. Such studies require a new technique that will allow comparing one-way speeds directly.

Before we discuss the basic idea, let us briefly state how the special theory of relativity (SR) deals with the empirical results of two-way speed comparisons. In SR, there is no length contraction in the rest frame because modifications of time and length in SR depend only on relative speeds. The fundamental hypothesis is SR is that the speed of light is a universal constant in all inertial frames, even though the experimental evidence is restricted to two-way speed comparisons. Therefore, the time taken to propagate a length *L* is always is L / c irrespective of whether the standard reference length is moving or not. Indeed, inertial motion is completely equivalent to a state of rest in SR. This implies that if it is possible to compare the one-way speeds in two opposite directions relative to a reference frame moving inertially at velocity *v*, the difference in time the two light pulses or wave-trains take to propagate a length *L* is expected to be null in SR. The expression in equation 9 is zero is special relativity.

Some earlier experiments

There have been no experiments that directly measured the one-way speed of light relative to a moving reference frame. However, some experiments have been interpreted by the experimenters as an effective measurement of the speed of the one-way propagation, or as a comparison of the one-ways speed in two opposite directions. Some of these measurements actually compare anisotropy of Doppler shifts of light emitted by moving sources and then try to interpret it as equivalent to a measurement of the anisotropy of the one-way speed of light. But most experimenters do not seem to realize that the old ether theory that has first order anisotropy in the speed of light relative to moving observers predict the same null results in such experiments, and therefore these are not experiments that can demarcate between Einstein and

Lorentz, or more generally, between special relativity and a theory of relativity with a preferred frame. We will briefly mention just one of these modern experiments to clarify that such experiments do not measure or compare the one-way speed of light.

Consider the experiment by Krisher et al that compared Hydrogen maser clocks separated by 21 km, stationary in earth's frame, using a stable fiber optical link[4]. Each clock generates a stable output signal at 100 MHz local frequency that is used to modulate a laser signal that passes from one clock to the other through the fiber optic link. If light takes additional path length along one direction compared to the other, due to the first order anisotropy, there will be fixed offset between the two clocks, which of course cannot be measured since there is no absolute synchronization. But if the anisotropy is time dependent, due to the rotation of the earth, then one can hope to see a time dependent phase difference between the two clocks, in the two channel network analyzers at each site, one channel fed by the local clock and the other by the signal from the distant clock. But, a dipole anisotropy signal was not seen even at the level of 1 part in 10^7. The quadrupole anisotropy was even smaller. What is forgotten in the analysis of such experiments is that the clock time dilation itself contains exactly the same term in the preferred frame theories, since the clock delays now depend on the absolute speed through the preferred frame, rather than on their relative speed[5]. Therefore, the clocks have different time dilations even when they are at relative rest. The time dependent phase change of the clock compensates exactly the time dependent delay in the propagation of the light, and the two cancel, and a null signal results. Therefore, these experiments do not test the anisotropy of the one-way speed of light, being affected by the first order time dilation of the source of the reference signal itself.

Measuring the one-way speed of light

It is possible to measure the one-way speed of light and other waves, and particles with just one clock, without the need to synchronize two distant clocks. The idea is extremely simple, and perhaps this is why it has been completely missed in the usual discussions. To see the point, consider the experiment discussed in the context of figure 1, but modified slightly as in figure 3.

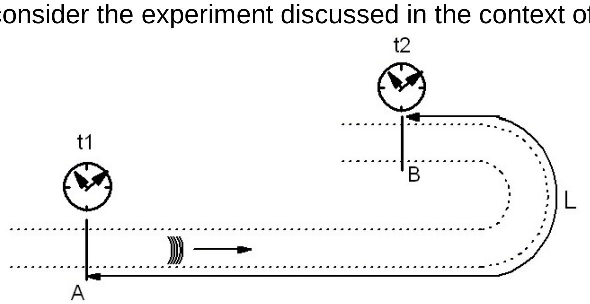

Figure 3: Measurement of the one-way speed along a curved track.

The comparison track is bent in a short section, but one is still measuring the one-way speed along the path from A to B. Note that the speed of the waves are not changing, and we have kept the total length to be traversed as *L* as in the previous experiments. In this experiment the results will be identical to the one obtained with the linear track. In fact, we are very familiar with this situation since this is how one-way sprint races are compared in situations where the track needs to be larger than about 100 meters.

Now consider the same situation where the start point A is moved to the right at speed *v* and the end point B is moved to the left with speed *v* synchronously. This can be achieved for measuring one-way speed of water waves, for example by connecting a string of fixed length between the two points and by pulling the two reference points together. This situation is exactly the same as the one in figure 2 as far as the measurement of the one-way speed is considered. All the reference markers in the observer's frame are moved in the same direction along the track at speed *v* such that by the time the wave reaches point B, it has moved by a distance *vt*, exactly the same way we had in figure 2. Again, the mathematical results are exactly the same as in the situation in figure 2. In particular, if we reflect the waves at B and perform a two-way speed measurement, the first order dependence on the velocity of the observer will cancel out and only second order differences will remain.

However, it is not possible to do the experiment for the case of light in this configuration for the simple reason that synchronous movement of the two reference marks require synchronizing signals to be sent between the two points. Behaviour if such signals in different theories are different and the analysis can become circular in logic. However, a simple modification eliminates this problem[6]. The modified configuration in figure 4 uses only one clock. The source, the detector, the clock etc. are all in the same frame, at the same reference point and yet, the experiment measures the one-way speed of the wave-train! This is achieved by bringing the point B so close to A, after winding once around the track, that they seem identical. It is important to note, however, that the physical distance from A to B is still L.

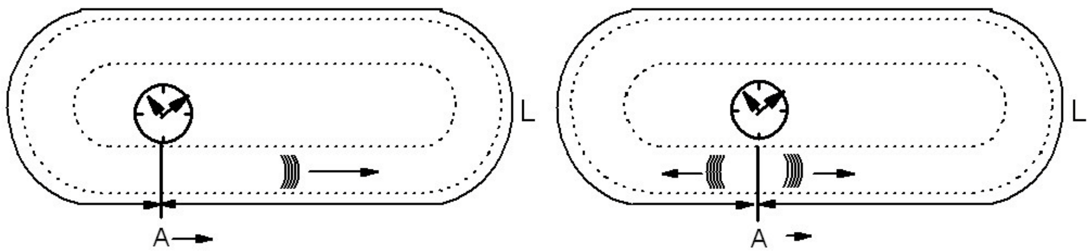

Figure 4: Measurement of the one-way speed using a single clock, relative to an inertially moving reference frame. See text for details.

In the left panel we have a measurement of the one-way speed of the wave-train, relative to an inertially moving reference frame A that carries just one clock. The panel on the right deals with the comparison of the one-way speeds of wave-trains in two opposite directions relative to a reference frame that is inertially moving in one direction with respect to some preferred frame. Note that the observer A is always in inertial motion during the experiment, since we assume that the speed of the waves is much larger than the observer's velocity; the waves trains reach back after one round trip in a time short compared to the time it takes for the observer to move a significant distance along the track. The second measurement of the comparison of arrival times can be done interferometrically, and then the clock is not required. One will monitor the shift in the interference fringes as the velocity of the observing frame with respect to the preferred frame is changed.

The prediction of special relativity in these situations is clear. Since the inertially moving observer is equivalent to an observer at rest, and since the speed of light is identical in both directions relative to the moving frame as well, the two wave-trains have to reach back simultaneously, as calculated in the rest frame of A. The distances from A to A along both directions are identical by construction, and if the speeds of the waves are also identical then the prediction of simultaneous arrival with respect to A is unambiguous (with respect to an external frame relative to which A is moving, the wave-trains will not reach simultaneously according to the theories of relativity we are comparing here).

The experiment

Ideally, the experiment has to be done with hollow optical fiber guides, all rigidly attached to a conveyor belt platform such that the platform on which the source and the detector for light are located moves linearly at uniform speed along one direction. The experiments that I have performed were either with normal optical fibers or in free space with reflecting mirrors. (It is easy to argue that all these configurations give the same result, though intuitively, and naively, one might want to argue that hollow optical fibers should be used, and this demand can be satisfied without much technical problems.) The configuration is shown in figure 5.

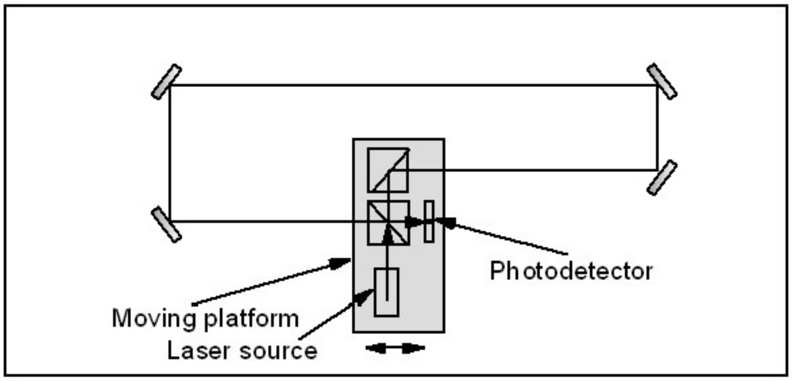

Figure 5: Schematic diagram of the experimental set up. The shaded rectangular region represents the moving platform on which the source, beam splitters and the detector are rigidly fixed. The four mirrors serve to fold the optical path.

The reference platform carried the source and the photo-detector. The moving platform is on a standard linear optical bench, with the movement made smoother by a layer of grease. A roller bearing optical stage with its springs removed and an air bearing stage have been tried as well. In the velocity range in which most measurements have been done (less than 1 m/s), the greased optical bench was sufficient. The sensitivity is sufficient to detect a shift that is less than $1/10^4$ of the width of the fringe, but the movement causes some vibrations and this limits the sensitivity to about 1/3000. This can be improved by a factor of 10 using essentially the same configuration by improving the stability of the fringes (the signal to noise at the detector is high enough to detect $1/10^6$ of a fringe, in principle). The total optical path is between 1.3 m and 2 m in the several runs conducted.

Ignoring second order effects, the expected shift in a preferred frame theory, in which the speed of light does depend on the velocity of the observer, can be calculated using the equation 9 for the arrival time difference. The optical path length difference with respect to the platform is

$$\delta l = c\delta T = \frac{2Lv}{c(1-v^2/c^2)} \simeq \frac{2Lv}{c} \qquad (10)$$

Then the shift in the fringe per meter of the optical path (*L*=1 m), for a wavelength of 633 nm is

$$\delta s = \frac{\delta l}{\lambda} = \frac{2Lv}{c\lambda} \simeq 0.01 \times v\ (m/s) \qquad (11)$$

We get a shift of about 1/1000 of a fringe when the speed is about 0.1 m/s. This is measurable and most of the data is taken with speeds in the range of 0.05 to 0.4 m/s.

The following graph (figure 6) summarizes the results from one such experiment, in which the arrival time difference of the wavefronts, δT, in the two directions is plotted as a function of the linear velocity of the reference platform. Clearly, the linear dependence on the velocity of the reference platform is unambiguously established. The line indicates the expectation in cosmic relativity in which the speed of light depends on the velocity of the reference platform. The same result is expected in the old ether theory as well, and the trend proves that the speed of light behaves in exactly the same way as the speed of other familiar waves behaves in relation to an inertially moving observer. Therefore, the special relativistic assertion of the universality and isotropy of the speed of light applies only to the two-way speed of light and not to the physical speed of light in one direction. This implies that the results of those experiments in which one-way speed becomes relevant, as in clock comparisons, the predictions of special relativity will not hold good, and this has already been pointed out and discussed in detail, with further empirical evidence[7].

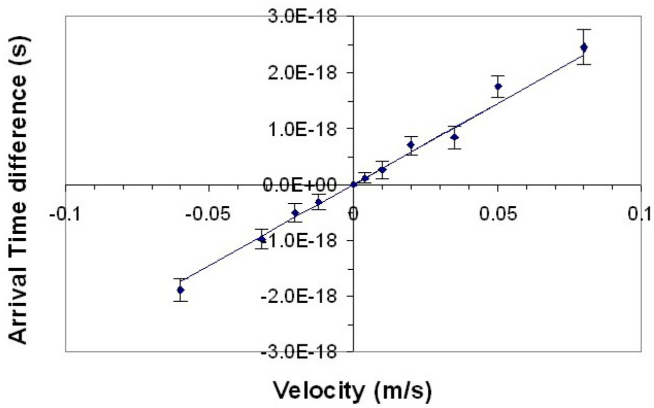

Figure 6: Arrival time differences between the wavefronts of light traveling in opposite directions relative to the inertial motion of the reference platform as a function of its velocity in the experiment depicted in figure 5. The time difference is derived from the shift of the interference fringes.

The experimental results are identical when an optical fiber is used, even though naively one might have expected that the optical phase difference would have been larger for a given velocity of the reference platform because light takes more time to complete the round trip. In the ether theory, there is a Fresnel drag that carried light in the fiber which compensates the time delay in the round trip. In Cosmic Relativity, the one-way speed of light in a moving frame is modified due to the gravitational vector potential $\vec{A}_g$ (or the off-diagonal metric components) generated by the matter current of the cosmos as seen in the moving frame, and therefore the modification of the round trip phase is simply proportional to the integral $\oint_{path} \vec{A}_g \cdot \overrightarrow{dx}$. This is the cosmic gravitational Aharanov-Bohm phase induced due to motion relative to the matter in the universe. This does not depend on the speed with which light completes the round trip, and also explains beautifully why the difference in the round trip time in the two opposite directions in optical as well as matter wave Sagnac interferometers is identical, and independent of the speed of the entity (photon, atom, electron etc.) circulating in the interferometer.

Conclusions

The experiment described in this paper, and its many possible variations, establish that the speed of light is not a universal isotropic constant relative to inertially moving observers. This finding invalidates the fundamental assumption of the special theory of relativity, and supports a theory of relativity with a preferred frame relative to which all velocities are to be referred for discussing velocity dependent physical effects like the time dilation. It is argued elsewhere that the preferred frame is the massive isotropic frame of the matter filled universe, and not the frame of the stationary ether[8]. All relativistic kinematical effects are in fact gravitational effects of the matter in the universe.

Therefore, the apparent success of the special theory of relativity is confined to situations involving two-way comparisons, or in those situations similar Lorentz factors on time and length cancel each other. There are several experimental situations where this does not happen, as in the measurements described here and in round trip clock comparison experiments described elsewhere[9], and then the results unambiguously suggest replacing special relativity with a theory of relativity in which the isotropic frame of the universe is the preferred frame. This new theory called cosmic relativity is described in detail in references 2 and 3. While it may be expected that such a paradigm change will take considerable time because it is difficult to change majority beliefs that are entrenched deep, the shift from special relativity to cosmic relativity is inevitable because unambiguous and new empirical evidence, apart from the requirement of consistency with the existence of a matter filled universe with its all pervading gravity, dictate such a change.

[1] C. S. Unnikrishnan, ‘Denying experience in the physical world: Consciousness misled’, to appear in the proceeding of the conference on Consciousness, Experience and Ways of Knowing: Perspectives from Science, Philosophy and the Arts (Ed. Sangeetha Menon, 2006).

[2] C. S. Unnikrishnan , ‘Cosmic Relativity: The fundamental theory of relativity, its implications and experimental tests’, E-preprint, available at http://xxx.lanl.gov, gr-qc/0406023 (2004).

[3] C. S. Unnikrishnan, ‘Cosmic Relativity: The only consistent ontological foundation for the theory of space-time and relativity’, to appear in ‘Foundations of Science’, Editor, B. V. Sreekantan (PHISPC, New Delhi, 2006).

[4] T. P. Krisher et al, Test of the isotropy of the one-way speed of light using hydrogen maser frequency standards, Phys. Rev. D **42**, 731-734 (Rapid. Comm.) 1990.

[5] References 2 and 3.

[6] I conceived this technique for measuring the one-way speed of light around the year 2000. Initially it was used as linear Sagnac phase detector in which the reference frame is inertial, in contrast to the conventional Sagnac interferometer. Soon it was realized that measurement of the phase difference is essentially the same as the measurement of time, once the frequency of the emitter is fixed. Then the measurement is also equivalent to a round trip clock comparison. Since the phase difference is equivalent to the difference in path length between the two propagation directions, the same experimental set up compares the one-ways speeds of light in two opposite directions relative to the inertial motion of the reference platform.

[7] References 2 and 3.

[8] References 2 and 3.

[9] C. S. Unnikrishnan, Discovery of a new cosmic gravitational effect revealed as the faster aging of a transported atomic clock, to be published. See also reference 2.