Theoretical Model of an Experiment to Test the Isotropy of the Speed of Light

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ABSTRACT

The value for the speed of light $c = 299,792,458$ m/s is widely known and used in theoretical physics, experimental physics, astronomy and astrophysics. However, this is the roundtrip speed from the source to the detector and back. The roundtrip speed of light has been verified thoroughly by several experiments to be a constant. Still, the equality of the one-way speed of light with the roundtrip speed of light, or the isotropy of the one-way speed of light, has never been verified. It is impossible to measure the one-way speed of light unless an absolute (standard) simultaneity is to be found. Yet, testing the isotropy of the one-way speed of light using a mathematical structure that resembles an isosceles triangle is still possible. Since the roundtrip speed of light has already proven to be isotropic, there are values only with which the one-way speed of light can travel in a path, maintaining the roundtrip speed of light to be isotropic. These values serve as limits to the maximum speed that the one-way speed of light can have in its direction of propagation in its path, from which two light pulses from both ends of its path send to the same clock, thereby evading the need for synchronization and allowing the possibility to test the constancy of the one-way speed of light.

Keywords: Isotropy, One-way speed of light (OWSL), Special relativity (SR), Two-way speed of light (TWSL).

1. Introduction

The measurement of the OWSL has been thought to be impossible to measure. The only thing that can be measured is the TWSL i.e. round trip speed of light. Albert Einstein chose a synchronization convention that made the OWSL equal to the TWSL. The constancy of the OWSL in any given inertial frame is the basis of Einstein’s Special Theory of Relativity. Experiments that attempted to directly probe the OWSL, independent of synchronization have been proposed, but none has succeeded in doing so [1] since Romer and Huygens measured the light speed by using the moons of Jupiter, to 1983’s 17th CGPM’s definition of the meter [2]. The speed of light is 299,792,458 m/s [3] which is almost equal to the calculated value of the speed of electromagnetic wave in vacuum by James Clerk Maxwell [4] and it has been verified with experimental results, but the experimental value is the average of the TWSL. By Einstein’s synchronization convention [5] it is believed that light travels at the same speed in all directions. But it is just a convention not an empirically verified fact. Slow clock transport tries to overcome this problem. Here if one clock is moved away slowly in frame $S$ and returned, then the two clocks will be very nearly synchronized when they are back together again. In the limit, as the speed of transport tends to zero, this method is experimentally and theoretically equivalent to the Einstein convention [6].

But if the OWSL is anisotropic, then the time dilation can no longer be ignored at smaller velocities, and slow clock-transport fails to determine the nature of OWSL. Therefore the OWSL cannot be observable except if absolute (standard) simultaneity is to be found [7]. However, that does not imply that we cannot know whether the OWSL is isotropic or not. Determining the OWSL has been studied considerably in the past. Michelson-Morley experiment and Kennedy-Thorndike experiment [8] have shown that the TWSL is independent of the closed path considered, and is isotropic. Although the average speed of TWSL can be measured, the OWSL is still undefined. Measuring the OWSL is almost
impossible, where closed paths are involved [9]. Ole Christensen Rømer’s experiment also thought that they have measured the OWSL. However, this experiment was carefully reanalysed by Zhang [10], who showed that they used the Jupiter system as a slowly-transported clock to measure the light transit times [11]. The Australian physicist Karlov also came to the same conclusion, after carefully re-analysing their experiment [12]. The NASA JPL team experimented by measuring the time of flight of light signals through a fibre optic link between two hydrogen maser clocks [13]. In 1992 the experimental results were analysed by Clifford Will who concluded that the experiment did measure the OWSL [14]. In 1997 the experiment was reanalysed by Zhang who showed that only the TWSL had been measured [15]. The Greaves, Rodriguez, and Ruiz-Camacho experiment [16] also thought that they measured the time of light in a single direction i.e. (OWSL). J. Finkelstein showed that the Greaves et al. experiment measures the TWSL [17]. The challenge in determining the one-way speed of any physical entity arises from the difficulty associated with synchronizing the clocks [18].

In this work, instead of two clocks, two laser pulses at both ends of the path are sent to the same clock, thereby evading the need for synchronization. The use of one clock is not a substitute for simultaneity, since the aim of this work is not to measure the one-way speed of light but rather to test the constancy of the one-way speed of light. Thus under the tight limits of the isotropic nature of the round trip speed of light regardless of the direction of propagation, we can test the equality of the OWSL with TWSL by sending an ultra-short laser pulse into a light tunnel that consists of photo-detectors at its both ends. On detection these photo-detectors trigger another two lasers whose pulses will be sent to an atomic clock as signals, this sequence occur twice one for the incident pulse and another for the reflected pulse. Hence there will be two readings in the clock, one for each direction. These values reveal the nature of the one-way speed of light.

This paper is structured as follows: in Section 2 The importance of performing this experiment to verify the constancy of the OWSL. In Section 3, The experimental methodology for the evaluation of the equality of the OWSL to the roundtrip speed. In Section 4 Testing a few cases as a thought experiment. Finally, Section 5 presents the summary and conclusion of this work.

2. Importance of Verifying the Constancy of OWSL

The one-way speed of light or any other physical entity (PE), is defined as the distance covered by that PE from one point to another in a certain amount of time. For PEs with a non-relativistic speed, it is easier to calculate the time by simply placing two clocks at both ends. But for the PEs with relativistic speeds, time dilation effects are prominent and for light, it is impossible to measure its one-way speed. The study of the small world and explanation of phenomena such as strong force, weak force and electromagnetic force are done by using the methods and techniques of the quantum theory. In contrast, the weakest fundamental force of nature Gravity is best understood by Einstein’s General relativity (GR) theory. Despite explaining the same reality, these two theories don’t fit together to form a single unified theory, as GR only works where gravitational effects are significant and at quantum scales the gravitational effects have little to no impact. On the other hand, quantum theory fails to explain gravity as it is the weakest among all the four fundamental forces of nature. Both of these theories and a few other fundamental constants depend on the constancy of the OWSL.

With this background, light could be a central piece that acts as a bridge between the quantum and the cosmic world. Light is an excitation of an electromagnetic field, better understood by quantum theory. The light emitted from an atom travels vast distances, interacting with celestial objects and also gets affected by strong gravitational fields, which are observed by telescopes. Even the distances of the celestial objects such as planets, stars, galaxies and galaxy clusters are measured and calculated assuming the constancy of the OWSL. Calculating the OWSL or confirming that the vacuum speed of light is indeed isotropic is of utmost importance in theoretical physics. This paper aims to provide a thought experiment in calculating the OWSL. There is no suggestion that Einstein is wrong or the OWSL could have a different value from the roundtrip speed value. Unless it is verified experimentally, it will become an empirically verified fact. As a matter of such importance, it should not be overlooked.

3. Experimental Methodology

A structure that resembles an isosceles triangle (both two sides and two angles are equal) [19] is constructed as shown in Fig. 1.

From Fig. 1, the triangle ABC has the angles $x = 45^\circ$, $y = 90^\circ$ and $z = 45^\circ$, where AB and BC have the same length. The light tunnels are placed along the AC, AB and CB paths as shown in Fig. 1. The Tunnel begins at ‘A’ and ends at ‘C’ and consists of Photodetectors [20] (PDs), two at both ends which detect the light pulse from the laser [21] and trigger a set of lasers, whose light pulses will be
sent as signals to the PD of the clock. When the clock receives a signal, it starts running from zero and it stops on the arrival of the second signal. This process happens twice, both for the incident and the reflected pulse. Hence, two readings in the clock will be observed, each one indicating the incident and the reflected pulse. When these two readings are added, they must be equal to the time taken for the light pulse to travel from A to C and C to A, which is the roundtrip time and as we know that the roundtrip speed is constant, the time taken for the round trip speed will also be constant and will be equal to the combined total of the two readings. The combined total of the time readings will always be equal to the roundtrip time, this holds even though OWSL is anisotropic.

3.1. Theory

The light pulse emitted from the source which is placed at ‘O’, moves along the path OACR. As the pulse reaches A and C it triggers another two laser pulses of the same frequency, whose paths would be AB and CB. The Clock is placed in the position of ‘B’. The first signal travels from A to C and then from C to the clock at B in the interval \(T_{AC} + T_{CB}\), while a signal from A to B reaches the clock in the interval \(T_{AB}\). The first measurement of the clock is the interval,

\[t_1 = T_{AC} + T_{CB} - T_{AB}\]  

As the light pulse reaches ‘R’, a reflector is placed at R, to reflect the light pulse along the path RCAD. And once again as the pulse reaches C and A, it triggers another two laser pulses, whose paths would be CB and AB. The reflected light signal travels from C to A and then from A to the clock at B in the interval \(T_{CA} + T_{AB}\), while a signal from C to B reaches the clock in the interval \(T_{CB}\). Thus the second measurement of the clock is the time interval,

\[t_2 = T_{CA} + T_{AB} - T_{CB}\]  

By adding (1) and (2), we get;

\[t_1 + t_2 = T_{AC} + T_{CB} - T_{AB} + T_{CA} + T_{AB} - T_{CB}\]

\[t_1 + t_2 = T_{AC} + T_{CA}\]

Here, \(T_{AC} + T_{CA}\) represent the roundtrip time \(T_R\), therefore;

\[t_1 + t_2 = T_R\]  

The roundtrip speed of light is constant, hence for a fixed length or distance the roundtrip time \(T_R\) is constant. For the anisotropic one-way speed of light case, \(t_1\) and \(t_2\) will not be equal to each other but they add up to give the same \(T_R\) value.

Thus if any variance exists in the one-way speed of light, it can be known from the \(t_1\) and \(t_2\) measurements. In such a case, if the \(t_2\) value exceeds the \(t_1\) value, i.e. \(t_2 > t_1\), then (3) needs to be modified into;

\[t_2 - t_1 = T_R\]  

By considering a particular length, the roundtrip time can be calculated for the light pulse, \(T_{R(cal)}\). Since the TWSL is isotropic regardless of the direction of propagation. Upon conducting the test \(t_1\)
and \( t_2 \) values are known. Based on these values either (3) or (4) is used to calculate the roundtrip time, \( T_R(\text{exp}) \) [since it is experimental \( T_R \) value].

Albert Einstein chose the synchronization convention that made the OWSL equal to the TWSL, i.e. for \( T_R(\text{cal}) \), \( t_1 = t_2 = t_0 \) and

\[
T_R(\text{cal}) = t_0 \quad \text{(5)}
\]

If the \( T_R(\text{exp}) \) is equal to or almost equal to \( T_R(\text{cal}) \),

\[
T_R\ (\text{cal}) = T_R\ (\text{exp}) + \Delta t
\]

where \( \Delta t \) will be the expected experimental error depending upon how precisely the experimental setup is built. Equation (6) represents that the TWSL is isotropic, and from \( T_R(\text{exp}) \) we can find the \( t_1 \) and \( t_2 \) values, thereby reconfirming the isotropy of the TWSL and also testing the constancy of the OWSL.

### 3.2. Conceptual Approach of the Experiment

Initially, the clock is set to zero. When the laser is turned on, a pulse of light takes the path of OACR and gets reflected as RCAO. A total of five Photo Detectors (PDs) PD1, PD2, PD3, PD4 & PDc (clock’s) are used, where PD1 = PD4 and PD2 = PD3 which are placed at the ends of the light tunnel along AC. The signals from the photodetectors to the clock are transmitted in the paths of ‘AB’ and ‘CB’. When the light reaches ‘A’ and interacts with the photodetector PD1, the detector triggers another laser whose light pulse will be sent as a signal to the clock. Meanwhile, the first light pulse moves to point ‘C’ and interacts with the detector PD2, which also triggers its laser and sends a light pulse as a signal to the clock. If either PD1’s signal or PD2’s signal reaches the clock first then the clock starts running. After some time the other signal will also reach the clock. Since the clock is already running, the time at which the 2nd signal arrived is recorded as the first reading ‘t1’ by the clock. This occurs twice one for the incident pulse and another for the reflected pulse, thus a second reading is also recorded by the clock ‘t2’.

Since ultra-short pulses are the events that take place in a time duration of the order of \( 10^{-12} \) seconds or less, the clock used must have a precision greater than or equal to \( 10^{-15} \) seconds to measure the time readings more precisely.

- **Fig. 2**-Interior view of the light tunnel, describes the hollow regions and the filled regions inside the tunnel. Here PD1 and PD3 are arranged at the ‘A’ end of the light tunnel along AC, whereas PD2 and PD4 are arranged at the ‘C’ end of the light tunnel along AC.
- **PD1** and **PD2** will detect the incident light pulse, which travels from point A to point C inside the light tunnel. PD3 and PD4 will detect the reflected light pulse, which travels from point C to point A inside the light tunnel.
- **In Fig. 3**, the green & red arrows indicate the direction and path of the incident & reflected light pulse respectively. The light pulse in the paths AB & CB travel in the same direction, for both the incident and the reflected pulse. The red & green marked lines at A and C represent PDs, which are placed at the opening and closing of the light tunnel along AC and upon detection, trigger a light pulse towards B.
- **The light pulse in the path AC travels in different directions**, for both the incident and the reflected light pulse. The light pulse is incident from the point ‘O’ onto point ‘A’, along the direction AC and gets reflected at the point ‘R’.
- **From Fig. 4**, it is shown that the signals from USLPG-1 and USLPG-2 in the paths AB and CB will also propagate in hollow tubes with vacuum conditions. Incident rays are shown as yellow rays and reflected rays as red rays. HPS is a circular ring-shaped object, whose circular radius is equal to, or slightly greater than the radius of the incident light pulse.
- **The direction of the light pulse only changes on the AC side of the triangle**, as the pulse goes in the path AC and reflects right back in the path CA. The light pulse in the paths AB and CB always travels in the same direction.
- **All the paths AC, AB and CB are enclosed within these light tunnels**, which provide vacuum-like conditions to cancel out unnecessary noise and reflections.
- **When PDc detects a light pulse**, it initiates the clock to start running from ‘0’, and upon the detection of the second light pulse it records the time reading as the 1st reading, ‘\( t_1 = T_{AC} + T_{CB} - T_{AB} \)’. Which is the time interval between 1st & 2nd signals.
- **This happens twice**, one for the incident light pulse and another for the reflected light pulse. For the reflected pulse it records the time as the 2nd reading, ‘\( t_2 = T_{CA} + T_{AB} - T_{CB} \)’. These two readings should add up to give the same \( T_R \) value, ‘\( t_1 + t_2 = T_{AC} + T_{CA} \)’ or ‘\( t_1 + t_2 = T_R \)’, even if they are not equal to each other. Only in the isotropic OWSL case, these two readings will be equal.
4. Test cases

Since the roundtrip speed of light is isotropic and is equal to ‘c’. Now we have fixed limits of the speed for the OWSL, 0.5c to ∞ and all the values in between.

Case 1

In this case, let \( M = 299792458 \) meters and the length of the light tunnel is \( \sqrt{2}M \) meters. In Fig. 5 light travels at the same speed in all directions. Therefore, \( T_{\text{R(cal)}} = 2.828427125s \). For the isotropic OWSL case, light travels with the same speed regardless of the direction of propagation. Hence the speed of light \( c = 299792458 \) m/s. The light pulse will take just one second to reach from A to B or B to C. Therefore

\[ T_{\text{R(exp)}} = t_1 + t_2 = 2.828427125s. \]

PD1’s signal reaches the clock first and the clock starts running from ‘0’, meanwhile the light pulse along AC also moves some distance ‘k’ meters.

The remaining distance in AC and BC takes a total time of; \( 0.4142135624s + 1 s = t_1 \)

From A to C, \( t_1 = 1.4142135624s \) and since it’s the isotropic case, \( t_2 = 1.4142135624s \) from C to A. \( T_{\text{R(exp)}} = t_1 + t_2 = 2.828427125s. t_1 = t_2 \) for isotropic OWSL case.

Case 2

In this case, \( M = 299792458 \) meters and the length of the light tunnel is \( \sqrt{2}M \) meters. In Fig. 6 light travels at different speeds in each direction as indicated by different coloured arrows. Now test for the anisotropic case of the OWSL. Therefore, \( T_{\text{R(cal)}} = 2.828427125s. \)

Note: In the anisotropic OWSL case the speed should not get below \( c/2 \) or if \( h \) is the speed then \( h < 0.5c \) is wrong because in this case to match up with the roundtrip speed of light, the \( h \) in the opposite direction needs to go beyond ∞, which is a contradiction. Thus the limits are set as \( 0.5c < c \).

Consider OWSL from A to C to be \( 0.6c \) which makes C to A to be \( 2.999999999c \). And OWSL along AB = 0.7c, along CB = 0.5c.
Here $t_1 = 2.357022604s$ and $t_2 = 0.471404521s$, ($t_2 < t_1$) $T_R = t_1 + t_2 = 2.828427125s$. Although the roundtrip value is isotropic, $t_1$ is not equal to $t_2$. The $t_1$ and $t_2$ values can be seen and recorded in real time by the clock. The equations above will help us to check if the experiment is working as it was intended to or not.

**Case 3**

In this case, $M = 299792458$ meters and the length of the light tunnel is $\sqrt{2}M$ meters. In Fig. 7 the light travels at different speeds in each direction and as indicated by the colours, the speed along CA & CB are the same. Therefore, $T_R(\text{cal}) = 2.828427125s$.

But the OWSL from A to C be $\infty$ m/s and C to A is 0.5 c. The speed of the OWSL along AB = 0.6 c and CB = $\infty$ m/s.
Here, as AC and CB speeds are $\infty$ the clock starts on the arrival of PD$_2$’s signal from C and stops when it receives PD$_1$’s signal from A. Therefore
\[ t_1 = 1.666666666666667\text{s} \]
\[ t_2 = 4.495093791412857\text{s}, \text{ since } t_2 \text{’s value is larger than } t_1 \text{’s (4) is used.} \]
\[ t_2 - t_1 = 2.828427125\text{s} = T_R \]
Due to phenomena such as Quantum Entanglement which appears to occur instantaneously regardless of the distance, this infinite speed case is considered.
Thus, different possibilities are demonstrated by the above test cases. And only in one case, the OWSL is isotropic. If OWSL is anisotropic there will be infinite combinations possible which still holds good for the isotropic roundtrip speed of light.

**Note:** Extremely precise clock \[\Delta_1\] and ultra-short laser pulse are required for accurate results, within the margin of the experimental error $\Delta r$.

### 5. Conclusion

A theoretical possibility of an experiment is demonstrated, specifically designed to find the nature of the OWSL, whether isotropic or anisotropic in addition to reconfirming the roundtrip speed of light to be isotropic. The challenge in determining the OWSL or any physical entity arises from the difficulty associated with clock synchronization; this work overcomes that difficulty by sending two light pulses to the same clock instead of using two clocks, thereby evading the need for synchronization. Though it is almost impossible to measure the OWSL or any other physical entity (PE) where the light or PE follows a closed path, the possibility to test the isotropy of the OWSL still exists. One such possibility is this work. This work aims to test the constancy of the OWSL by also acting as a testing method for Einstein’s Special Theory of Relativity, which depends on the constancy of the OWSL. By reconfirming the isotropy of the TWSL, this work concludes by verifying whether the OWSL is isotropic or anisotropic.

**Data Availability Statement**

Data sharing is not applicable to this article as no new data were created or analyzed in this study.
Author declares no conflict of interest.

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