Experimental Determination of the Speed of Light

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Abstract

The goal of this experiment is to determine the speed of a traveling light wave using the time-of-flight method. We allow a beam of light to travel a known distance and measure the time it takes, giving us the velocity.

1 Introduction

The speed of light is an incredibly important universal constant, used in many equations throughout the fields of quantum physics, electrodynamics, and relativistic mechanics. Many of the current theories of gravitation and quantum gravity hinge on the value of the speed of light. Light, depending on the circumstances, can be percieved as both a wave and a particle (called a photon). In the lab setting, light is interpreted as a beam of photons, emitted by the laser in a specific direction.

One of the main assumptions in this experiment is the idea of two-way and one-way speed of light. It is currently only reasonable to measure what is called the two-way speed of light, the speed of light traveling in one direction, and then back the opposite direction. Physicists cannot be certain that the speed of light is not different based on the direction, even though it seems unlikely.

In this experiment, we measure the two-way speed of light using short LED pulses, by measuring the time light takes to travel a known distance, and Equation (1).

$$c = \frac{\text{distance}}{\text{time}} \tag{1}$$

2 Procedures and Data

There are two measurements required to determine the speed of light in this experiment, the distance traveled, and the time to travel. The experimental setup consisted of a base unit (BU), the device emitting and recieving the pulses of light, at a fixed distance from a Fresnel lens (FL). A Fresnel lens

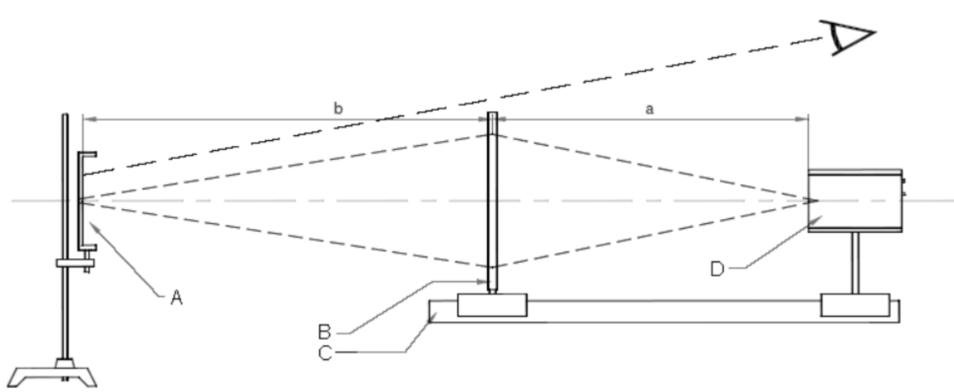

Figure 1: Experimental setup of the base unit (D), the Fresnel lens (B), and the reflector panel (A). Image taken from reference [1]

is designed to collimate a light beam. The light beams emitted from the base unit are at a variety of angles, but once they pass through the Fresnel lens, the beams are aligned parallel to each other, creating a more focused and thus easily detectable beam of light. On the opposite side of the Fresnel lens from the base unit is a reflector (R), to send the light beam back to the base unit.

In addition, the base unit is connected to a conventional oscilloscope at three ports, each with a specific function. When emitting a pulse of light, the base unit also sends what is called the "reference

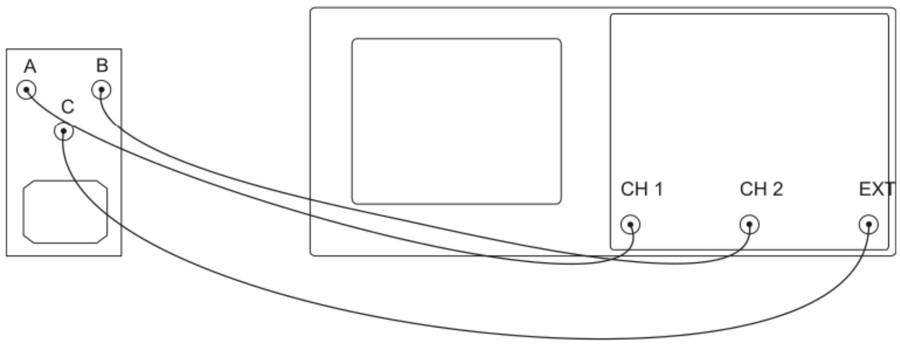

Figure 2: Connections between the base unit (A, B, and C) and the oscilloscope (CH1, CH2, and CH3). Image taken from reference [1]

signal" through port A. When the base unit receives the returning light beam, a signal is emitted through port B. Port C is the triggering signal to help the oscilloscope accurately read the signals.

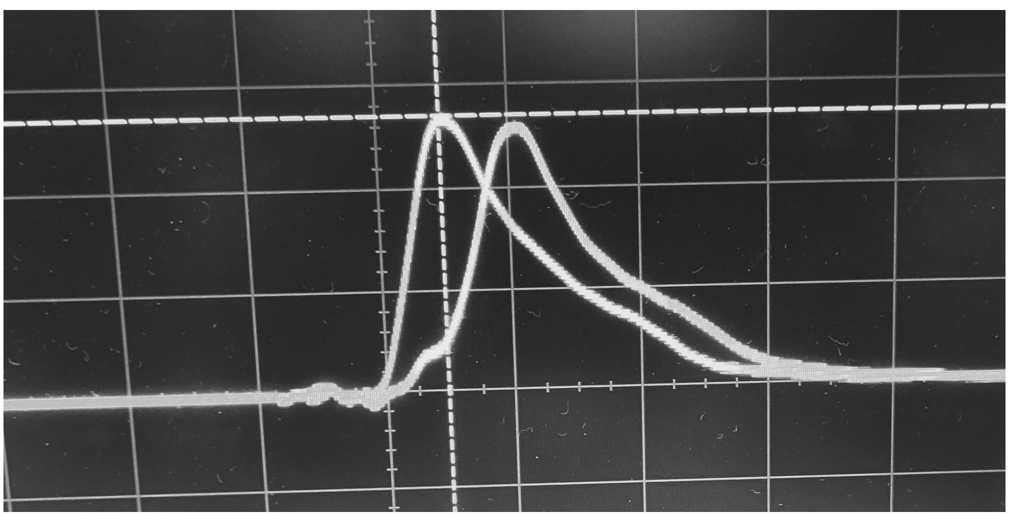

Figure 3: Oscilloscope displaying the peaks representing the reference signal (left peak) and the returning signal (right peak). The time difference between these peaks is the time light traveled from the base unit to the reflector and back.

In order to determine an experimental value for the speed of light, light beams were measured traveling different distances. The outgoing and returning light beams would be represented as two peaks on the oscilloscope. Since the peaks had similar shapes and widths, we measured the time difference between the peaks in order to get the time traveled. The measured times on the oscilloscope fluctuated, so we measured five different values of the travel time for each difference, and averaged to get a more accurate measurement. The uncertainty was determined by the spread of values.

Using these times, we were able to compute the speeds for each distance (using equation (1)), for further analysis. The uncertainties in table 2 were determined using error propagation.

Distance BU to R (cm ± 0.1)	t1 (ns)	t2 (ns)	t3 (ns)	t4 (ns)	t5 (ns)	Average Time (ns)
302.2	5	6.9	8.5	5.6	6	6.4 ± 0.875
407.4	12.5	15.6	10.6	9.0	10.6	11.66 ± 1.5
501.0	17.2	19.5	16.2	15.6	17.2	17.14 ± 1.0
599.6	20.4	20.3	19.6	19.5	18.8	19.72 ± 0.5
699.6	22.7	22.6	25.0	21.9	23.4	23.12 ± 0.8
799.0	25.0	27.3	28.1	29.7	25.0	27.02 ± 1.0

Table 1: Recorded travel distances and times

Distance BU to R (cm ± 0.1)	Computed Speed of Light (m/s)
302.2	$47 \pm 6 \quad \times 10^7$
407.4	$35 \pm 4 \quad \times 10^7$
501.0	$29 \pm 2 \quad \times 10^7$
599.6	$30.4 \pm 0.8 \quad \times 10^7$
699.6	$30 \pm 1 \quad \times 10^7$
799.0	$30 \pm 1 \quad \times 10^7$

Table 2: Calculated speeds for each data point

3 Analysis

Multiple types of analysis were performed in order to frame the data set in a variety of ways. The first was a simple linear fit, used to determine the speed of light in the whole experiment. In theory, the line should pass through the origin, but often times the experimental data does not quite match. Due to this, I performed two linear fits, one that passes through the origin, and one that does not.

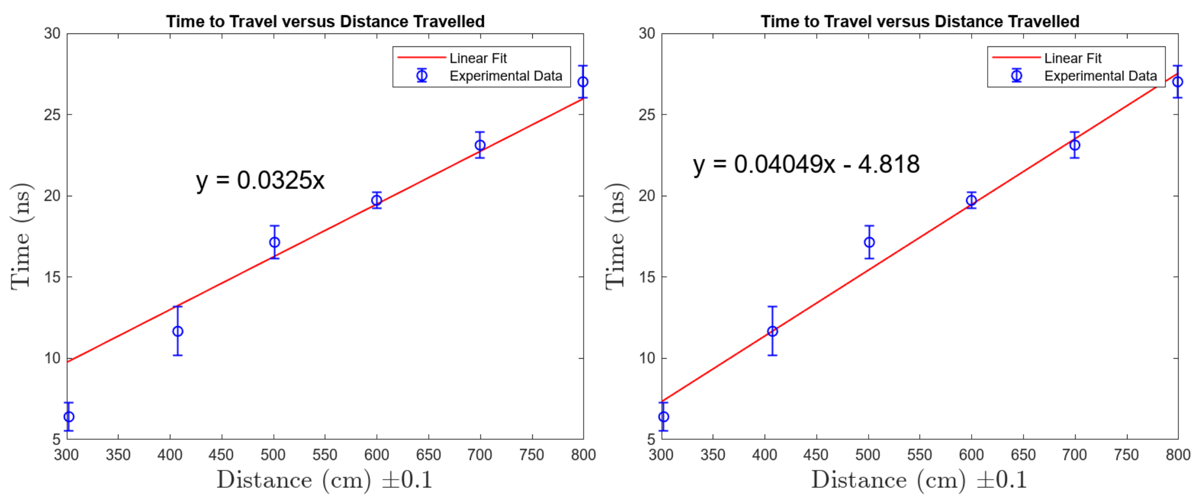

Figure 4: Linear fits of the experimental data, with a proportional fit (left), and a general linear fit (right). The error in the fits is 5%

The slopes of the linear fits have units of nanoseconds per centimeter, meaning the slopes represent the inverse of the speed of light. The proportional fit then gives $c = [3.0 \pm 0.2] \times 10^8$ m/s, and the linear fit gives $c = [2.5 \pm 0.1] \times 10^8$ m/s. Compared to the accepted value of $299,792,458$ m/s [2], the percent errors are respectively 0.06% and 16.6%. Clearly the proportional fit (Fig. 3, left image) is a better match for finding the speed of light.

In addition to performing a linear fit, I calculated individual values of c for each measurement. This set was analyzed to find the mean, standard deviation, and the standard deviation of the mean (SDOM) (using equations 4.5, 4.9, and 4.14 in [3]). As can be seen, the mean average of the computed values is decently close to the speed of light, with a percent error of 12%. An example calculation of

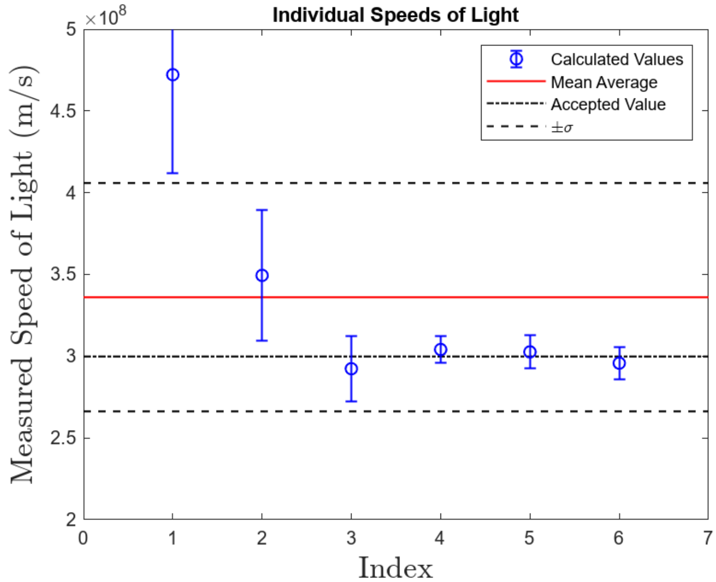

Figure 5: Individually computed speeds of light (with index on the x-axis). Plotted with lines representing the mean average (top line) and the accepted value of c (bottom line)

the mean is shown:

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{n} x_i = \frac{47.2 + 34.9 + 29.23 + 30.41 + 30.26 + 29.57}{6} \times 10^7 = 3.36 \times 10^8 \qquad (2)$$

The standard deviation is one order of magnitude less than the mean, which makes sense, and the SDOM provides our uncertainty in the mean, giving a final value of $c = [3.4 \pm 0.3] \times 10^8$. As stated before, this has around a 12% error, making the proportional fit still the most accurate estimate of the accepted speed of light.

I have also plotted the individual data points in a graph, along with horizontal lines representing the accepted value, and the mean average.

mean ($\bar{x}$)	3.36	$\times 10^8$
standard deviation (σ_x)	6.98	$\times 10^7$
SDOM ($\sigma_{\bar{x}}$)	2.85	$\times 10^7$

Table 3: Analysis performed on the data set of individual speeds of light from each measurement

4 Conclusion

The speed of light is one of the most difficult physical properties to measure, so much so that we have never satisfactorily measured the speed in one direction, instead relying on reflective surfaces. In this experiment, the speed of light was measured using a pulsed laser, a Fresnel lens, and a reflector to direct the light back for measurement. The oscilloscope records two peaks, one for the emitted light, and one for the returning pulse. We measured the speed of light with a 0.06% percent difference, although it is worth mentioning that the linear fit was forced to intersect the origin. As can be seen in Figure 4, the first two measurements were very inaccurate, but the last four were extremely close to the accepted value.

In addition, an SDOM analysis of the data was performed, giving a mean value with a 12% difference from the accepted value. The most prominent source of error in this experiment was the oscilloscope. The time traveled fluctuated wildly, especially at shorter distances, and this can be seen in the data. As well as this, the experiment was performed in a lab setting, but the object was to measure the speed of light in a vacuum. It may be interesting to explore how the index of refraction in air plays a role in this experiment.

References

[1] 3. S. GmbH, *Equipment set for measuring the speed of light*, 3B Scientific Physics (Hamburg, Germany, 2016).

[2] P. J. Mohr, B. N. Taylor, D. B. Newell, and et al., *Crc handbook of chemistry and physics*, edited by W. Haynes, 95th ed. (CRC Press, 6000 Broken Sound Parkway NW, Suite 300, Boca Raton, FL, 2014).

[3] J. R. Taylor, *An introduction to error analysis :* 2nd ed. (University Science Books, Mill Valley, Calif : c1982.).