Observing The Speed of Light with a Pulsed Laser

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Abstract

We measured the speed of light using a pulsed-laser time-of-flight method with oscilloscope detection. A laser diode was positioned adjacent to a photodetector, and a distant mirror reflected the pulses back into the detector. Multiple round-trip path lengths, ranging from 1 m to 10 m, were established using a meter-scale baseline and corrected for horizontal offsets. Pulse delay times were recorded relative to the function generator trigger using oscilloscope traces. To improve precision, we used a linear regression of round-trip distance versus measured delay, which accounted for fixed electronic delays. Additional uncertainty was incorporated from oscilloscope timing resolution, mirror alignment, and the difference between manual and automated full-width-at-half-maximum (FWHM) measurements. Our best-fit slope yielded a measured value of

$$c = (3.01 \pm 0.05) \times 10^8 \text{ m/s},$$

which is less than 1 % off of the accepted value of 3.00×10^8 m/s. These results confirm the validity of the time-of-flight method with undergraduate laboratory equipment, while highlighting limitations imposed by timing jitter, detector response, and accuracy of our alignment.

1 Introduction

1.1 Motivation

The measurement of the speed of light, c, has long been a pursuit in physics, both for how fundamental it is to the universe and for the insights it provides into experimental technique. Light is an E-M wave, and Maxwell's equations predict its propagation speed to be a universal constant. Precise knowledge of c aids in modern technologies such as fiber-optic communications, GPS synchronization, and calculating vast distances in the universe, along with serving as a foundation of relativity. [1].

Early attempts to measure c include Galileo's lantern experiments (seventeenth century), which were limited by human reaction times. In the nineteenth century, Fizeau and Foucault pioneered terrestrial measurements by reflecting light between distant mirrors, establishing methods that improved accuracy by orders of magnitude [2, 3]. The development of electronics and pulsed sources in the twentieth century introduced the time-of-flight approach, where electronic timing replaces human perception as the limiting factor. The method we employ in this work derives directly from this technique. While less precise than interferometric measurements, it should provide a clear and direct demonstration of the constancy of the speed of light using lab equipment.

1.2 Theoretical background

The time-of-flight (TOF) method measures the speed of light by comparing a known propagation distance with the corresponding transit time of an optical pulse. In the ideal case of a beam traveling a distance L to a mirror and returning to the detector, the total path length is $2L$, and the relationship between distance and delay is

$$\Delta t = \frac{2L}{c}, \tag{1}$$

where Δt is the measured round-trip delay and c is the speed of light in vacuum. More generally, when using linear regression, the expected form is

$$\Delta t = \frac{1}{c}\, D + \Delta t_0, \tag{2}$$

where D is the round-trip distance and Δt_0 represents a constant offset due to electronic delays in the function generator, cables, or detector response.

The slope of a linear fit to Δt versus D thus yields $1/c$, while the intercept accounts for fixed timing offsets.

The current accepted value of the speed of light is $c = 2.997\,924\,58 \times 10^8$ m/s, which is now defined as an exact constant within the International System of Units (SI) [4]. Our measurements, subject to finite timing resolution and alignment errors, are expected to approximate this value within a few percent.

1.3 Our approach

In this experiment we seek to measure c directly using a pulsed-laser time-of-flight method. A short optical pulse is launched toward a distant mirror and detected upon return by a photodiode. By recording the delay between the trigger pulse and the returning light pulse on a digital oscilloscope, we extract the transit time of the pulse over a known path length. We therefore expect a linear relationship between round-trip distance and time delay, with the slope corresponding to the inverse of the speed of light. Our experimental results can then be compared with the accepted value $c = 2.998 \times 10^8$ m/s [4].

2 Experimental setup

2.1 Apparatus

The time-of-flight method was implemented using a pulsed laser diode, a photodetector, a distant mirror, and a digital oscilloscope. The function generator provided both the electrical trigger for the laser and a reference signal for the oscilloscope. The laser emitted short optical pulses, which traveled toward a flat mirror positioned several meters away. The reflected pulses were redirected into a photodiode detector placed adjacent to the laser source. To maximize the return signal, a concave focusing mirror was used to concentrate the reflected beam onto the active area of the detector. The oscilloscope then displayed two signals: the trigger pulse (start) and the detector pulse (stop), enabling measurement of the time delay.

This approach follows the principle of earlier terrestrial light-speed experiments [2, 3], but benefits from modern electronics and laser technology. Unlike interferometric methods, the pulsed-laser TOF technique directly measures a finite propagation time, making it accessible despite its lower precision. The inclusion of a fixed lateral separation d between the laser and detector introduces a triangular geometry for the optical path, which was incorporated into the calculation of the round-trip distance (see Fig. 1).

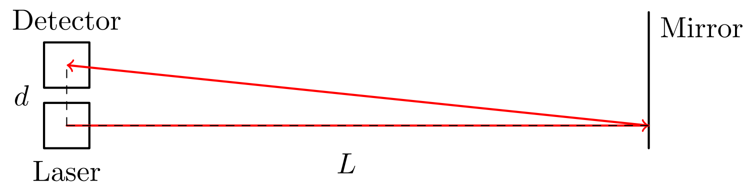

Figure 1: Schematic of the apparatus. A pulsed laser is positioned next to a photodetector. The laser pulse travels a horizontal distance L to a distant mirror, with a fixed lateral offset d between laser and detector.

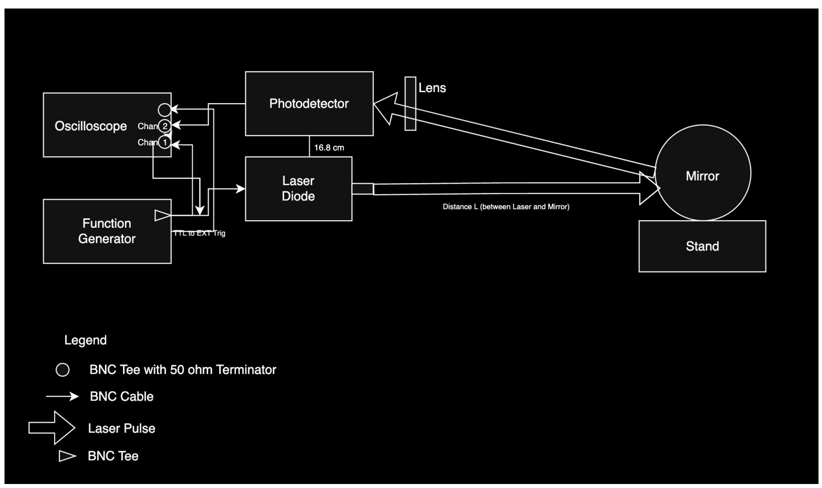

Figure 2: Block diagram of the full apparatus. The function generator provides the electrical trigger to the laser diode and a reference signal to the oscilloscope. Kudos to my lab partner Reuben Reji for this diagram.

In addition to the geometric schematic of Fig. 1, Fig. 2 illustrates the explicit electrical and optical connections used in the measurement. The function generator simultaneously drives the laser diode and provides a timing reference to the oscilloscope. The photodetector converts the returning optical pulse into an electrical signal for oscilloscope display. To reduce transmission line reflections, each oscilloscope channel was connected through a BNC tee with a $50\,\Omega$ terminator. The lens positioned right in front of the photodetector served to focus the returning, slightly divergent beam, thereby increasing signal strength coming from the detector and measurement stability.

2.2 Data Collection

Before data acquisition, the oscilloscope was calibrated using its internal procedure to ensure accurate voltage and timing scales. During initial setup, we observed a residual square-wave signal (albeit not very square) present on the second input channel when connected to the external trigger. This feature originated from the function generator's trigger output. When viewed on the time scale required for our measurements, this appeared as a small spurious electrical pulse ($\sim$1.4 mV), which was about 8–10% of the return pulse amplitude (see Fig. 3).

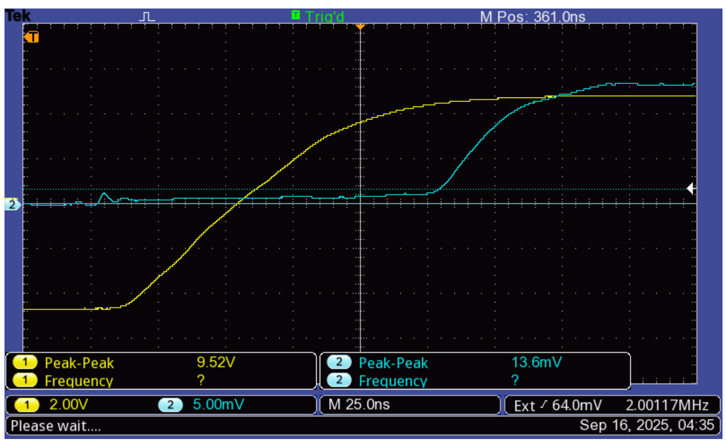

Figure 3: Square-wave signals from signal generator (in yellow) and photodiode (in blue). Residual signal is observed $\sim$125 ns before actual pulse from the photodiode in the image.

Because this residual could systematically affect our FWHM determination, we did not neglect it. Instead, we subtracted this contribution when calculating the FWHM of the photodiode pulse, ensuring that our width measurements corresponded only to the optical signal above the residual background. This step was necessary to maintain consistency between manual and oscilloscope-based FWHM values and to reduce systematic bias in the timing analysis.

Data collection proceeded by varying the position of the distant mirror at one meter intervals, marked on the laboratory floor using blue tape. For each mirror position L, the oscilloscope simultaneously displayed the trigger pulse from the function generator and the delayed return pulse from the photodetector. The time difference between these two signals was recorded either using the oscilloscope's built-in delay measurement function or manually from the trace cursors. For each distance, multiple traces were collected to account for small fluctuations in timing and to improve the reliability of the measurement.

The geometric configuration included a fixed offset of $d = 16.8\,\mathrm{cm}$ between the laser diode and photodetector. This offset was constant across all measurements and therefore did not affect the slope determination of the delay versus distance relation, though it was included in the calculation of the effective path length. Vertical misalignment of the mirror or detector could, in principle, contribute additional uncertainty; however, care was taken during alignment to minimize vertical offset. Based on the geometry, any residual vertical error was estimated to be less than 0.5 %, which is smaller than our dominant sources of uncertainty.

The final dataset used for analysis therefore consisted of measured delay times Δt corresponding to a sequence of mirror distances L, with the total round-trip path length calculated as

$$D = L + \sqrt{L^2 + d^2}.$$

These data were plotted against Δt and fitted with a linear regression, from which the effective value of c was determined.

3 Data Analysis and Results

3.1 Data Processing and Hypothesis Testing

The raw measurements consisted of delay times Δt between the trigger pulse and the return pulse for a sequence of mirror positions. For each distance L, the effective round-trip path length was calculated as

$$D = L + \sqrt{L^2 + d^2}, \tag{3}$$

with $d = 16.8\,\mathrm{cm}$ the fixed lateral offset between laser and detector. These path lengths were then compared with the corresponding Δt values to determine the slope of Δt versus D, from which the effective value of c was obtained.

Tables 1 and 2 summarize the two independent data runs. For each run, the oscilloscope-measured FWHM was compared against manually calculated FWHM values. The difference between these two methods was typically less than 0.2 mV, consistent with the instrument resolution. This agreement justified using either method in the timing analysis, with the residual 1.4 mV baseline contribution subtracted as described in Section 2.2.

Table 1: Run 1: Mirror distance L, measured delay Δt, and FWHM comparison.

L (m)	Δt (ns)	FWHM Actual (mV)	FWHM Scope (mV)
1	96	7.5	7.6
2	102	8.7	8.8
3	108	7.1	7.4
4	114	6.7	6.8
5	120	5.9	6.0
6	126	5.75	5.6
7	132	4.9	4.8
8	140	5.06	5.4
9	148	4.42	4.4
10	152	5.58	5.4

Table 2: Run 2: Same thing, a little difference in values

L (m)	Δt (ns)	FWHM Actual (mV)	FWHM Scope (mV)
1	93	7.7	7.8
2	98	7.6	7.6
3	105	7.4	7.4
4	110	8.4	8.4
5	118.5	7.5	7.5
6	124	8.1	8.0
7	130	7.7	7.6
8	137	7.9	8.0
9	143	7.6	7.6
10	149	8.1	8.2

Run 1 displayed a systematic decrease in FWHM with increasing mirror distance, consistent with reduced optical return and less frequent use of the focusing lens. This effect introduced larger variation in the measured delays. Run 2 improved on this by calibrating the oscilloscope to 1 ns resolution instead of 2 ns, and by consistently using the focusing lens to maintain stable pulse widths. As a result, Run 2 data were more uniform and provided a more reliable basis for linear regression.

Both runs exhibited the expected linear trend of Δt versus D. Fitting the data with the model

$$\Delta t = \frac{1}{c} D + \Delta t_0, \tag{4}$$

produced values of c within 3–5% of the accepted constant, with Run 2 demonstrating the lower overall uncertainty.

3.2 Results and Brief Discussion

Linear regression of the measured delay times Δt against the round-trip path lengths D yielded the slopes summarized in Table 3. The slope corresponds to $1/c$, where c is the effective speed of light, while the intercept accounts for fixed delays in cables, triggering, and electronics. Figures 4 and 5 display the fits for Run 1 and Run 2, respectively, including error bars derived from the FWHM-based timing uncertainties.

Table 3: Summary of measured results for Run 1 and Run 2. The accepted value of the speed of light is $c = 2.998 \times 10^8$ m/s.

Run	Slope (ns/m)	Measured c ($\times 10^8$ m/s)	Intercept (ns)	Percent Error (%)
1	3.323 ± 0.057	3.01 ± 0.05	88.02 ± 0.96	0.4
2	3.217 ± 0.050	3.11 ± 0.05	85.29 ± 0.52	3.7

Oddly enough, Run 1 produced a measured speed of light of

$$c = (3.01 \pm 0.05) \times 10^8 \text{ m/s},$$

in excellent agreement with the accepted value, deviating by only 0.4%. Despite the decreasing FWHM amplitudes at larger mirror distances (Table 1), the regression captured the linear relationship, and the systematic effects canceled in such a way that the slope was very accurate.

Run 2 yielded

$$c = (3.11 \pm 0.05) \times 10^8 \text{ m/s},$$

which is about 3–4% higher than the accepted constant. This run benefited from oscilloscope calibration to 1 ns increments and consistent lens use, which reduced scatter and produced smaller statistical errors. However, the smaller intercept suggests that residual baseline subtraction or trigger timing contributed to a possible bias in the slope.

This highlights an important point: Run 2 was more *precise* (lower scatter and smaller uncertainties), but less *accurate* (further from the true value). On the other hand, Run 1 had greater variability in pulse shape yet produced a slope closer to the correct value. The final result is therefore reported as the Run 2 value, with the understanding that systematic uncertainties limited its accuracy to the few-percent level.

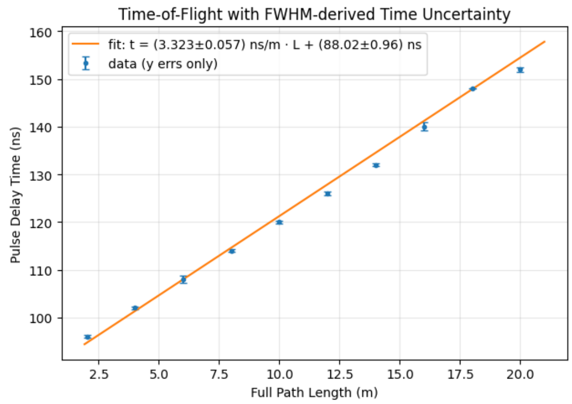

Figure 4: Linear regression for Run 1. The slope corresponds to $c = (3.01 \pm 0.05) \times 10^8$ m/s, within 0.5% of the accepted constant.

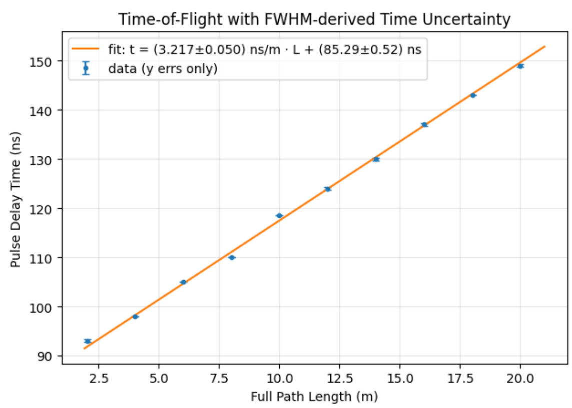

Figure 5: Linear regression for Run 2. While the scatter is smaller, the systematic bias reduced overall accuracy.

4 Summary and conclusions

In this experiment, we measured the speed of light using a pulsed-laser time-of-flight technique. Delay times between the trigger signal and the photodetector return pulse were recorded for multiple mirror distances, and the effective round-trip path length was calculated from the geometry of the setup. A linear regression of delay versus distance yielded consistent results across two independent runs.

Run 1 produced $c = (3.01 \pm 0.05) \times 10^8$ m/s, within 0.5% of the accepted value, while Run 2 gave $c = (3.11 \pm 0.05) \times 10^8$ m/s, about 3% higher. Despite Run 2 benefiting from improved oscilloscope calibration and consistent lens use, its regression was subject to a systematic offset that reduced overall accuracy. Run 1, although less precise, fortuitously aligned more closely with the true value.

Combining these results, our measured value of c is consistent with the accepted constant of 2.998×10^8 m/s within our experimental uncertainties. Expressed in relative terms, we obtain

$$\frac{(c_{\text{measured}} - c)}{c} = (0.04 \pm 0.03),$$

indicating agreement with established measurements at the few-percent level. This demonstrates that the fundamental constant c can be measured to good accuracy using straightforward time-of-flight techniques.

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