The Speed of Light

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We measured the speed of light in an experimental apparatus against the constant value, c, 299,792,458 m/s. Instruments used to measure the speed of light included a light emitting diode (LED), a photomultiplier tube (PMT), and fast pulse circuitry. Measured speeds of light using leading edge linear fits were $(3.06\pm0.16)\times10^8$ m/s and $(3.13\pm0.50)\times10^8$ m/s for the applied pulse widths of 2 ns and 40 ns. Conversely, using asymmetric Gaussian fits, the speed of light measurements were $(3.01\pm0.04)\times10^8$ for 2 ns and $(2.97\pm0.02)\times10^8$ for 40 ns.

Background

The method of measuring the speed of light used in this study is modeled after the Foucault method, which used an apparatus containing sets of mirrors to project and measure light. The projected light reflects off a rotating mirror, to a fixed mirror, back to the rotating mirror, finally to a detector. The apparatus was optimized by Albert Michelson in the 1920's and experimentally measured the speed of light to an error of ±4 km/s [1]. Apparatuses such as the Foucault apparatus allow for measuring the speed of light in a laboratory.

Apparatus

The experimental apparatus replicates the Foucault instrument, but without the rotating reflector. Values of the speed of light were measured with different applied pulse widths. Components include the time-to-amplitude converter (TAC), Multi-Channel Analyzer (MCA), and the computer program (MAESTRO) [2]. It is important to note that the medium inside of the enclosed tube is air rather than a vacuum. As the name suggests, the TAC converts the pulse time into positive amplitude pulses whose pulse height is proportional to the time difference between the start time (t_{start}) and stop time (t_{stop}). Concurrently with the positive amplitude pulses, negative amplitude pulses are sent directly to the TAC, generating t_{start}. Photons emitted from the LED source travel the length of the tube and are transmitted to the PMT, which are then converted to t_{stop} in the TAC. Photons from a second source are collected from reflections off the Fresnel lens. Both reflection phenomena generate two peaks, one with a relatively lower count rate in the respective amplitude bins. The MCA records the TAC signals and distinguishes the counts across 2048 channels. MAESTRO compiles all amplitudes with corresponding channels and generates histograms, also providing ASCII data. Components of the instrument are specified in figure 1.

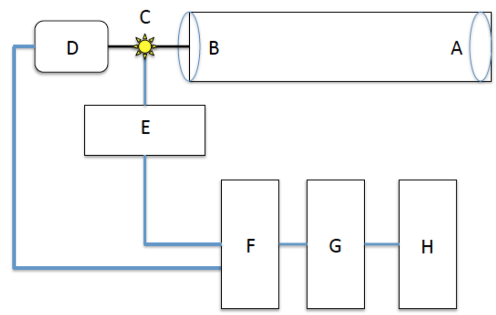

Figure 1. *A) Mirror, B) Fresnel lens, C) LED Source, D) PMT, E) Pulser, F) TAC, G) MCA, H) MAESTRO. [3].*

Procedure

Table I. *Initial Apparatus Parameters*

Applied Pulse Widths to LED (ns)	Tube Length (m)	MCA Channels (sec.)
4 & 20	11.3183±0.0013	2048

The experiment uses a yellow LED emitting photons into the an enclosed tube [3]. Emitted photons initially traveled through a Fresnel lens located in the enclosed tube, which also reflected photons. These photons were detected first by the PMT at an earlier time, t_1. Photons that were not backscattered pass through the Fresnel lens and were reflected off the mirror, A[1], on the back of the enclosed tube. The reflected photons were then detected at a delayed time, t_2. Photons were then converted

[1] Corresponds to labels (A-H) in Figure 1

into electrons via the photoelectric effect. Ultimately the pulses and the electrons were then converted into amplitude using the TAC and then split over multiple channels in a histogram compiled with MAESTRO.

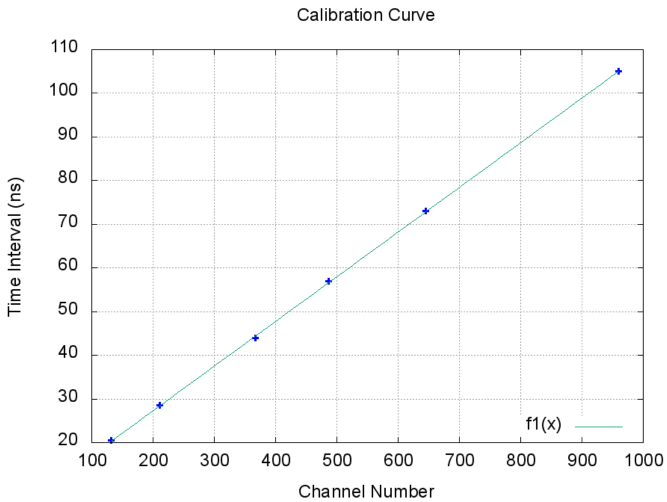

Figure 2. *A calibration curve for the TAC. The linear fit represents a correlation calibration between channel number and time.*

Using the delay box, a calibration curve was compiled to represent the time interval (Δt) versus the MCA channel number for six unique time intervals. A linear fit of the six time intervals were used to convert the channel numbers for the difference in time between the histogram peaks generated by MAESTRO. Resulting time for the peak difference was utilized along with the measured enclosed tube length to determine an experimental estimate of the speed of light.

Two trials of different pulse widths were conducted for 2 ns and 40 ns. Nothing except the pulse widths were manipulated during this study to represent a fixed system with one changing parameter.

Calculation of Results and Errors

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

The measured speed of light, c, was calculated using equation 1. The variable, L, in the same equation represents the distance from the Fresnel lens to the mirror. Input parameters are shown in table 1. MAESTRO provided an ASCII data file resulting in figures 3 to 6. The set of figures show two peaks for both the 2 ns and 40 ns applied pulse settings.

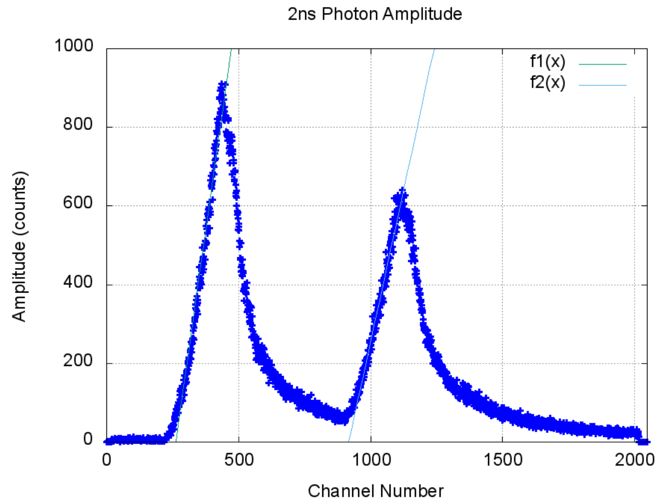

Figure 3. *MCA channel distributions for a 2 ns LED pulse setting with two leading edge linear fits.*

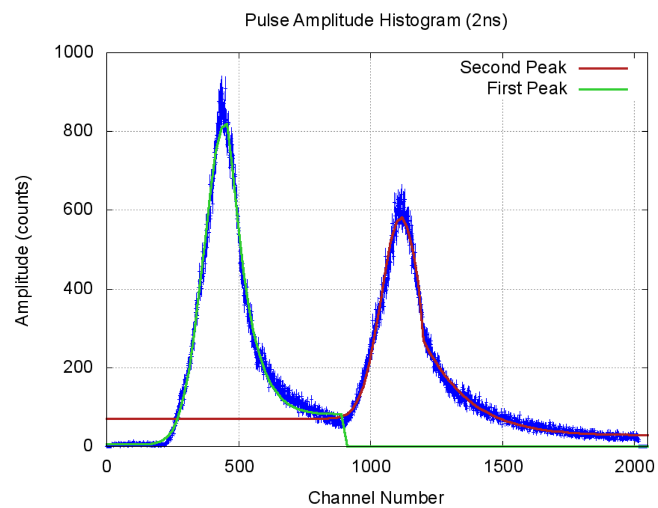

Figure 4. *MCA channel distributions for a 2 ns LED pulse setting with asymmetric Gaussian fits.*

The two peaks correlate to the time of initial detection of reflected photons off the Fresnel lens, and the final detection of photons from the mirror at the back of the tube. Linear regressions were fit to the ascending slopes of the two peaks. The variance between the linear fits provided the difference in channel numbers for the two-photon detection phenomena. The channel difference was calibrated with the calibration curve to output a time difference, Δt. Using the initial length of the tube and time differences resulted in a measured speed of light using equation 1.

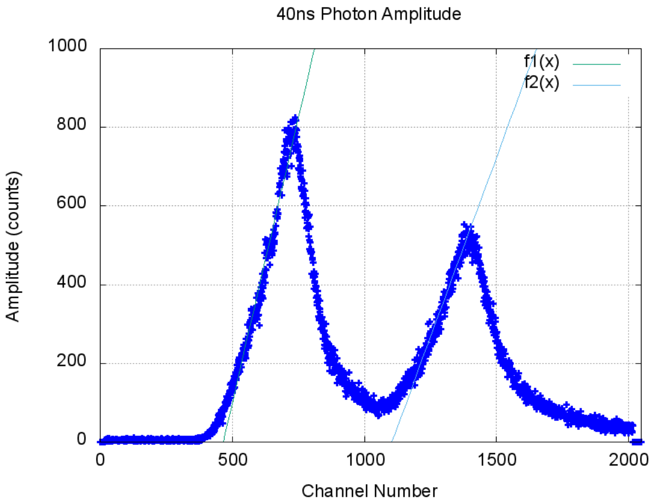

Figure 5. *MCA channel distributions for a 40 ns LED pulse setting with two leading edge linear fits.*

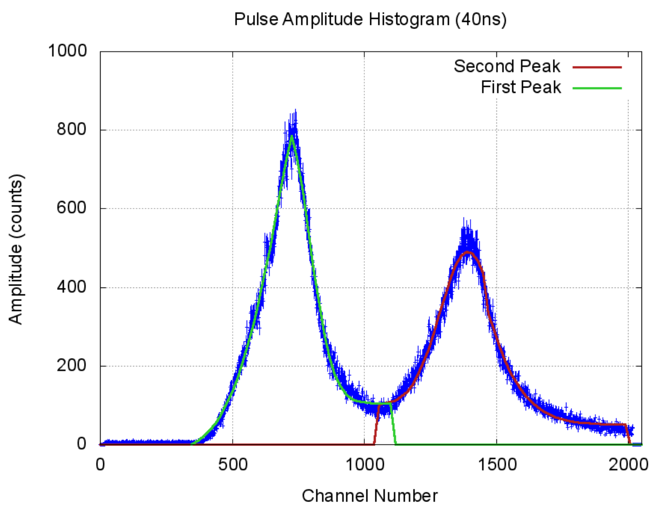

Figure 6. *MCA channel distributions for a 40 ns LED pulse setting with asymmetric Gaussian fits.*

Experimental Values of the Speed of Light

The experimental speed of light measurements using the leading edge linear fits were $(3.06\pm0.16)\times10^8$ m/s and $(3.13\pm0.50)\times10^8$ m/s for the 2 ns and 40 ns respectively. Additionally, using asymmetric Gaussian fits generated speed of light measurements of $(3.01\pm0.40)\times10^8$ and $(2.97\pm0.18)\times10^8$, again for 2 ns and 40 ns respectively.

Table II. *Values of c with linear and Gaussian fits*

Applied Pulse Width to LED (ns)	Fit Type	Speed of Light (m/s)	Percent Error (%)
2	Linear	$(3.06\pm0.16)\times10^8$	2.11
40	Linear	$(3.13\pm0.50)\times10^8$	4.54
2	Guassian	$\mathbf{(3.01\pm0.04)\times10^8}$	**0.31**
40	Gaussian	$\mathbf{(2.97\pm0.02)\times10^8}$	**1.06**

The main source of error is attributed to systematic error. The data consists of many points with corresponding errors in amplitude; therefore the systematic error was determined with Poisson error. The employed method consisted of measuring the width of the data points before the peak. The width included points which enclosed the data and represented systematic error.

Table III. *GNUplot generated errors for 2 ns applied pulse widths for both fits*

	First Peak	Second Peak
Slope[a]	4.77±0.05	3.09±0.04
y-intercept[a]	-1252.70±18.88	-2839.74±42.42
Channel Numbers[b]	448.46±8.91	1116.82±0.7754

Complete error propagation included the channel number difference of the linear and Gaussian fits and the calibration curve, also including the Poisson systematic error. Raw data from the fitting program yielded values and corresponding uncertainties shown in table 3. Compared to the true speed of light, c, the experimental speeds are within the experimental error, with the favored method being asymmetric Gaussian fits.

Discussion

Measured speeds of light were determined to be similar to the theoretical speed of light. The double linear fits provided channel differences leading to a stable estimate of the time difference. Asymmetric Gaussian fits were significantly more accurate for the applied pulse widths, relative to the leading edge linear fits, bringing percent errors below 2%. Length of the tube was affected by extra slack in the measuring tape. In conclusion, the measurements of speed of light deviated from the accepted value of, c, but the experimental values are well within the systematic uncertainty.

[a] Leading edge linear fit
[b] Asymmetric Gaussian fit

[1] McFarland, Kevin. "Speed of Light Demonstration by the Foucault Method." University of Rochester. Web. 5 Nov. 2015.

[2] "Multichannel Analyzer (MCA) Application Software." Nuclear Applications Software—ORTEC Scientific Equipment. ORTEC. Web. 5 Nov. 2015.

[3] THE SPEED OF LIGHT. (n.d.). Retrieved November 4, 2015, from `http://www.phys.hawaii.edu/~teb/phys480l/SpeedOfLight.txt`