Measuring the Light Speed Constant Using a Modified Foucault's Method

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ABSTRACT

In this experiment, we demonstrate a simple alternative method to the well-known Foucault's method for measuring the light speed constant. A method similar to a paper entitled "Foucault's Method in New Settings"[1] has shown a result within 1 percent of the accepted value of the speed of light. We will not show a method as accurate but more rigorous in that it took a considerable amount more of coordination and alignment techniques to produce meaningful results.

1 Introduction

In the 17^{th} century, Galileo performed his experimental method in order to measure the speed of light by measuring the time it took for his assistant to send back a signal to Galileo after opening a lamp's shutter. The experiment was of course was overall inconclusive but birthed the conclusion that light (if not an instantaneous speed) was quite expedient. Foucault's method, first developed in 1892, is one of the most well-known methods of determining the speed of light as it uses simple lab equipment like a mirror spinning at a frequency to produce a value for the speed of light. The method is based on the fact that if a light beam bounces off a spinning mirror twice, the mirror will have deflected a delectably minute angle by the time the beam strikes it a second time given the distance from the light source to the detector is sufficient. This deflection results in a small displacement of the final beam in comparison to where it originally struck the detector[1]. We can measure the speed of light from the measured displacement, and the length of the round-trip path or twice the total optical path length.

The equation below can be used to determine the speed of light:

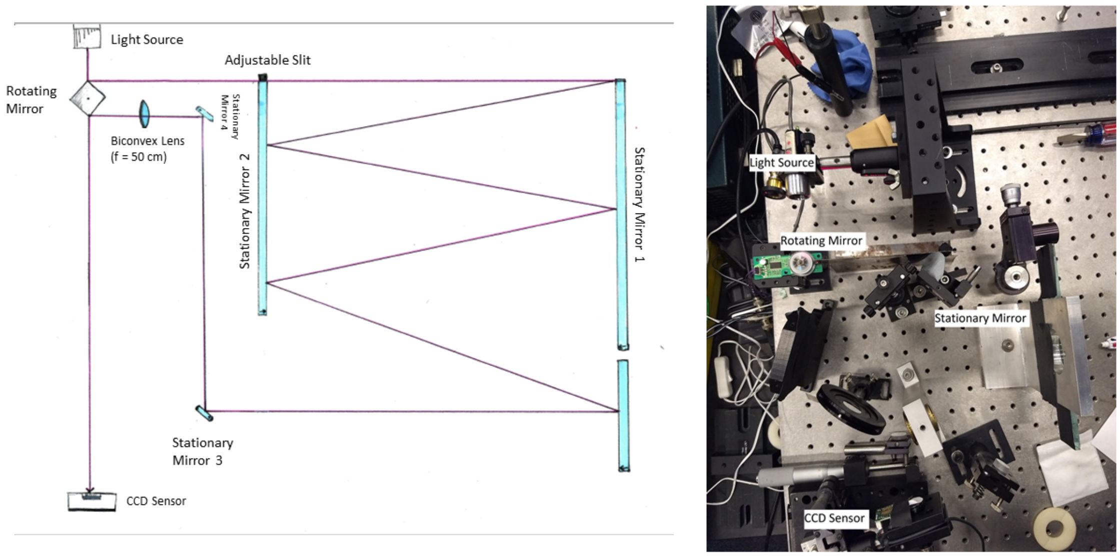
$$c = \frac{8\pi(d_1)(d_2)(\Delta\omega)}{\Delta s} \tag{1}$$

Where d_1 - distance from source to the rotating mirror, d_2 - distance from rotating mirror to the CCD/webcam (d_1 subtracted from the total optical path length), $\Delta\omega$ - angular velocity of spinning mirror, Δs - separation between source and final laser and c is the light speed constant.

2 Experimental Setup

In our original experimental setup, we attempted to use a centrifuge, on its center a modified mirror that spun according to the preset frequency of the housing. However, it was difficult for us to align the light beam due to its size and vertical distance from the optical table. In addition, the centrifuge was also loud at higher frequencies and posed a slight safety hazard. We, therefore sought alternative options and later decided to use the rotating mirror from a laser printer. The mirror from the laser printer is smaller, not as loud as the centrifuge, and posed virtually no safety risk given our purposes. Moreover, it was capable of reaching a higher rotation frequency than the centrifuge.

Thus, we powered a four-sided rotating mirror with an integrated circuit from a laser printer in our final experimental setup. We also used a CCD sensor from an old Logitech webcam with 640 by 480 resolution to capture the images, as well as a red laser diode as our light source. The figure 1 below displays our final set up in detail. The light beam first hits the rotating mirror, then reflects and passes through an adjustable slit. The beam then hits the Stationary Mirror 1 (SM 1), and is reflected between SM 1 and SM 2 four times. After that, the beam is allowed to reflect off SM 3 and to SM 4. At this point, the reflected beam goes through a lens with a focal length of 50 cm. This beam is directed to hit the rotating mirror and strike the CCD sensor. We decided to let our light beam reflect back and forth four times between SM 1 and SM 2 because of limited space on the optical bed. This resulted in a total optical path of around 9 meters.



(a) (b)

Figure 1. (a) This diagram shows our final set up with 4 stationary mirrors, 1 rotating mirror, 1 lens, and 1 CCD sensor. (b) This picture displays the actual positions of the light source, the mirrors, and the CCD sensor on the optical bed.

To confirm the speed of the rotating mirror, we utilized a function generator to send signal input to the integrated circuit which running the spinning mirror, as well as a photodiode detector connected to an oscilloscope to determine the frequency of the mirror. To do this, we made the light beam strike the rotating mirror once and reflect toward the detector. The detector picks up potential spikes periodically and then sends these signals back to the oscilloscope which we can use to determine the rate at which the signal is detected.

After determining the frequency of the rotating mirror, we set up the experiment as shown in Figure 1 (a). The design is fairly straight-forward and results in the ability to capture images of the final beam with the CCD sensor as shown in Figures 3 (a), (b), and (c). From there we were able to determine the distances between beam spots for different speeds of the rotating mirror and thus our value for the speed of light.

3 Result

With the collected measurements from the oscilloscopes, we were able to demonstrate a linear relationship between the input frequency signal and the frequency of the spinning mirror. By using an oscilloscope to measure the frequency, we determined that 679.9 Hz or 680 Hz is the highest input frequency to drive the rotating mirror. However, it is important to note that this is not the frequency at which the mirror is rotating. Additionally, we also learned that 200 Hz input is the lower bound of frequency capabilities for the mirror to rotate stably. Figure 2 below helps to confirm our measurement. At an input of 680 Hz, we measured 952.4 Hz as the rotational frequency for our mirror. Similarly, we obtained a rotational frequency of 465.8 Hz and 378.8 Hz at the 350 Hz and 220 Hz input frequencies respectively. However, because our rotating mirror is four-sided, we had to divide our measurement by 4. Thus, our final collected rotational frequency is 14,286 RPM, 6,897 RPM, and 5,682 RPM for 680 Hz, 350 Hz, and 220 Hz input respectively. Notice that in Figure 2, the last three data points converge to roughly around 980 Hz when reaching any frequencies that are higher than 700 Hz. Hence, we believe 680 Hz is the maximum input frequency that can drive the rotating mirror stably.

With our setup it is nearly impossible to determine shift between the original beam and the reflected beam as we had proposed in our initial formulation of this experiment. This is due to the sweeping that results from measuring and placing the mirrors on the plane of rotation of the mirror. Thus, we decided to compare the shifts between the curves of 3 different speeds of the rotating mirror. We captured 10 frames of 3 different input frequencies (680 Hz, 350 Hz, and 220 Hz) by using the CCD sensor (webcam). Figure 3 (a), (b), and (c)) show the images that were

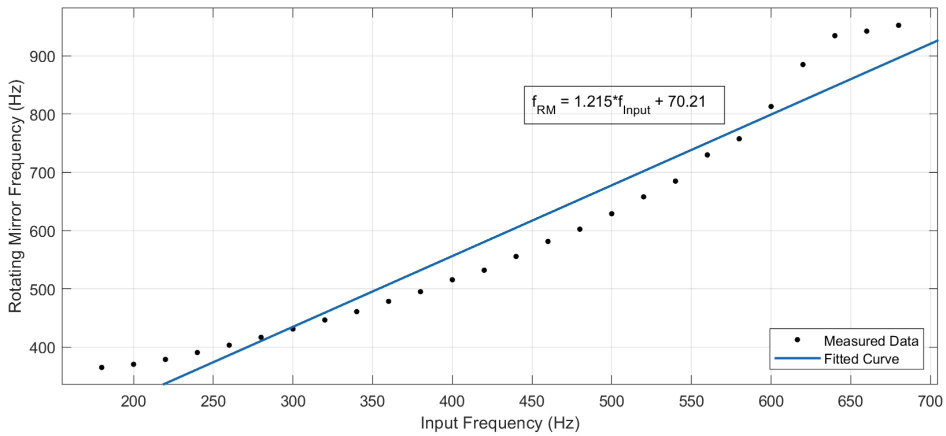


Figure 2. rotational frequency of rotating mirror as a function of the input frequency. The equation in the figure display a linear relationship between the 2 frequency.

captured by the CCD sensor with color-scaled. These figures clearly imply that the deflected distance is very small, and we cannot physically measure them because they are on the order of microns. In addition, we decided to take the average of 10 frames for each frequency in order to acquire precise measurements (see Figure 3 (d), (e), and (f)).

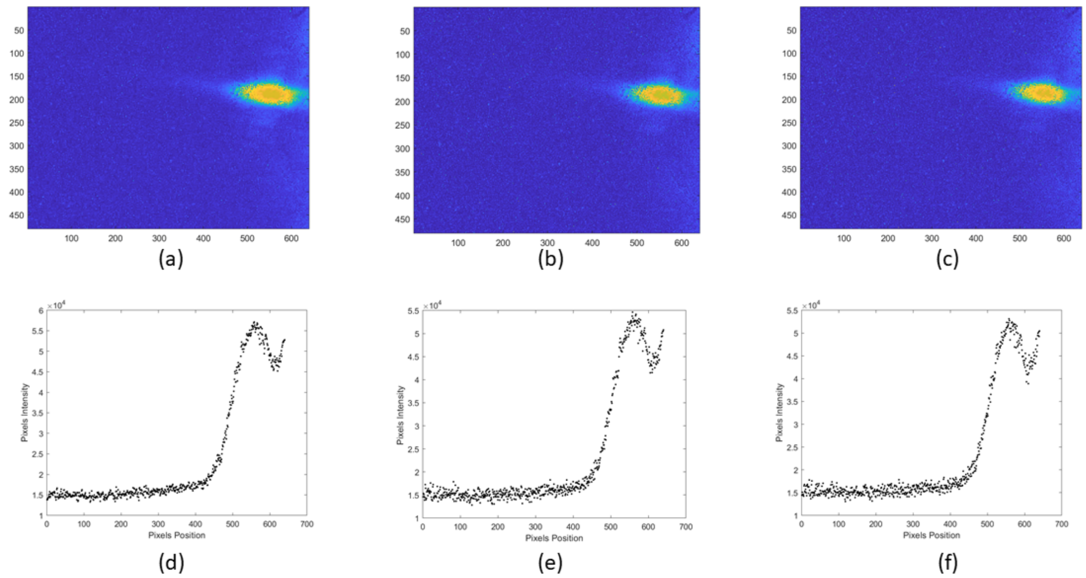


Figure 3. Figures (a) 680 Hz (b) 350 Hz (c) 220 Hz are color-scaled for the distribution of light's intensity in our captured images. Figure (d) 680 Hz, (e) 350 Hz, and (f) 220 Hz display the distribution of pixels and the intensity based on grey scale. We can see that the most intense area of the 3 figures are in the range of 550 to 570 pixels.

Curve fitting was used for determining the location of the beam. We decided that the Gaussian model is the best fit for our collected data. Figure 4 allows us to calculate a small shift between the three curves. We found that between 680 Hz and 350 Hz, there is a 2 pixel shift between beams. Additionally, between frequencies 680 Hz and 220 Hz there is a 3 pixel shift. To convert pixels to a physical measurement, we measured the dimensions of the CCD knowing the pixel density. Each pixel of our CCD sensor represents roughly 10 micrometers of distance. Thus, our measured deflected displacements are 20 micrometers and 30 micrometers.

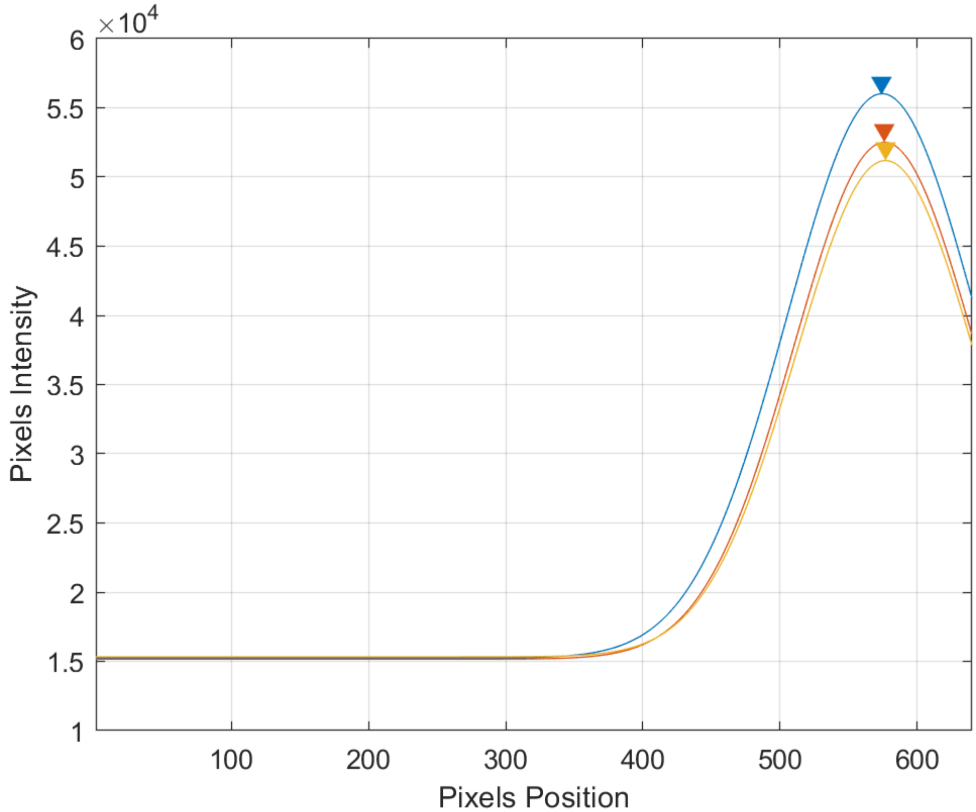


Figure 4. Gaussian fit for the curves shown in Figure 3 (d), (e), and (f) respectively. The blue curve represents 680 Hz, with the peak at 574 pixels. The red curve represents 350 Hz, with the peak at 576 pixels. The orange curve represents 220 Hz, with the peak at 577 pixels. We use these Gaussian curves to find the approximate location of the distance of each respective frequency

Following equation (1) above, we find from our calculations that the light speed according to each of our frequency differences and their corresponding phase shifts is as follows:

Frequency Difference ($\Delta\omega$)	Phase Shift	Calculated c
680 Hz - 350 Hz	20 μm	295,103,935.1 $\frac{m}{s}$
680 Hz - 220 Hz	30 μm	274,238,000.3 $\frac{m}{s}$

Table 1. Calculated Results with Collected Measurement

To find the conclusive overall average of the light speed constant, according to our setup in 1 (a), we execute a simple averaging operation for both measured light speeds to ensure accuracy, and arrive at a constant of 284,670,967.5 $\frac{m}{s}$. This may be expressed in units of c as the decimal 0.949560 c. Where the constant c is the accepted speed of light taken to be 299,792,458 $\frac{m}{s}$. Comparing our result to the known value of the speed of light, our result had approximately a 5% error.

4 Conclusion

We were able to identify the different potential sources of error. For example, light beam reflections around the equipment during the experiment can affect the alignment process. In addition, the CCD could pick up a different reflected beam from the other metal equipment instead of the beam we want to measure. This could potentially give us inaccurate measurements later. To limited the potential sources of error for the project, we recommend shiny metal surfaces be covered by tape or other non-reflective materials.

We could not do more measurements with different colored lasers as proposed due to the laser being fixed and having a very careful calibration and alignment that would take significantly more time to re-setup. We learned that alignment is extremely important in a project that in which optics and moving parts are integral to the experiment. Also, other colors of monochromatic light such as green and especially blue, pose quite a safety hazard we successfully evaded.

In conclusion, we were able to measure the speed of light to a reasonable accuracy, 0.95 c, under time and equipment constraints for the purposes of scientific measurement and experience in a lab environment.

References

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