Experimental Observation of the Speed of Light Using a Rotating Mirror Setup

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The speed of light is a fundamental concept in many fields of physics. Although light travels at a very high speed, we can utilize the finite speed of light to our advantage by having it reflect on a rapidly rotating mirror, travel some length and back, and reflect back at the mirror at some different final angle. Repeating this process for a different rate of rotation allows us to observe the minuscule difference between the reflected points. Using a telescope to observe that small difference and, by deriving a formula, we can calculate for the speed of light. Here we present a measurement of the speed of light c to be (3.2 ± 0.2)E8 m/s via a weighted average calculation from two different lengths light traveled and a propagation-based error analysis accounting for each component affecting the final reported value. Our result demonstrates a 6.0% difference from the accepted value of $c = 299792458$ m/s. To this end, we conclude with a discussion on the methods of improvement.

I. INTRODUCTION

The speed of light was first measured, albeit unintentionally, by Danish astronomer Ole Roemer in 1676. By observing when Io, a satellite of Jupiter, was eclipsed, Roemer noted that there was a consistent deviation in the time of the observation based on the position of Earth relative to Jupiter.[1] Eventually, another scientist, Christiaan Huygens, found Based on Roemer's data that the speed of light was approximately $2.1E8$ m/s.[1] Although this value is notably lower than the accepted value of $c = 299792458$ m/s,[2] it helped break the false assumption that the speed of light is infinite. Since then, more accurate measurements of the speed of light have been made, in which it has served as cornerstones of numerous fields in physics. Most well-known perhaps is in Einstein's Theory of Special Relativity, in which c in a vacuum must be consistent for all inertial frames of reference.[3] Given this applicability, the purpose of this work is to provide a measurement of the speed of light using a telescope, a rotating mirror apparatus with other reflective mirrors, and varying lengths traveled by light.

II. THEORY

The main idea behind this lab experiment is that given some angular frequency of a rotating mirror, the angle for which light makes contact with the spinning mirror will be slightly different compared to that after it travels a round trip of some distance $2L$, which we note as θ_m (mechanical angle) $= \omega dt$ and the time for travel $dt = \frac{2L}{c}$. We observe this slight difference in angle, which causes a small displacement of the point which light reflects on an observed surface, with a telescope of some focal length f, in which the mechanical angle $2\theta_m = \theta_o$, the optical angle. Figure 1 represents this concept.

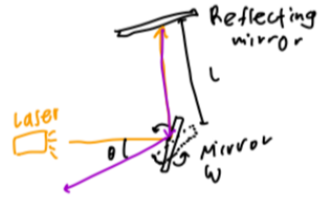

FIG. 1: Rotating mirror setup

Note that the small change in distance can be represented by the formula $d = f\theta$, whereby f is the focal length of the telescope. By varying the ω of the rotating mirror, we change the small displacement that occurs, and by observing this small difference in displacement, we can solve for the speed of light. The formula that we use after accounting for the round trip and rearranging the variables is

$$c = \frac{4\omega L f}{d}, \tag{1}$$

whereby c is the speed of light, ω the angular frequency, f the focal length of the telescope, and d the displacement of the light observed via the telescope. A note on ω, however, is that the apparatus recording the rotation of the two-sided mirror reported its value in frequency f, and to be expressed in w, we used the formula $w = \pi f$.

In addition to the small displacement idea, another key concept underlying this lab experiment is the focal length of the telescope used to observe this small displacement. In essence, a telescope has some magnification ratio $M = \frac{S_i}{S_o} = \frac{h_i}{h_o}$, in which S stands for distance and h the height. X_i stands for that for the image, from the telescope, and X_o for that of the object. As it is impossible to measure the image distance within the telescope (S_i), we resorted to measuring h_i, h_o, and S_o and used the formula below to solve for the focal length of the telescope.

$$f = \frac{MS_o}{1+M}. \tag{2}$$

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III. APPARATUS & PROCEDURE

The apparatus used for this lab consists of a fixed laser that is directed toward a rotating two-sided mirror with a selectable ω, in which a light sensor placed next to the rotating mirror recorded the number of times light registered on it, and converted it to frequency. After its initial contact with the mirror, it travels up to a series of periscopes that allow the light to travel some distance L. Note that the all of the angled mirrors are adjustable, but the dotted ones are the ones that were manipulated for this lab. By adjusting the angles, we controlled how many times the laser was reflected across the hallway. Figure 2 below shows a schematic diagram for the lab apparatus.

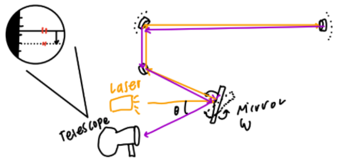

FIG. 2: Schematic diagram for the lab apparatus

We measured the change in d for two different ω values, in which we used the formula $d = \frac{0.001n}{39.97}$ to convert from the n number of turns on the dial to meters. The end of the brightest segment of light was set as the reference point for the dual measurements. Note, then, that the formula for c from Equation 1 should be adapted as

$$c = \frac{4\Delta\omega L f}{\Delta d}. \tag{3}$$

The length L that light travels was measured by breaking the down the path the light travels as the following. Note that for $L_1 \rightarrow L_4$ we measured with a measuring rope and recorded its uncertainty. For the Hallway measurement, we recorded each tile for its length and uncertainty and multiplied the number of tiles to both values. Note that for day 1, we only had the light reflect back and forth once, while for the second day we made it do it twice, thus the length of the Hallway will double.

L_i	Measurement (m)	Uncertainty (m)
L_1	0.984	0.005
L_2	1.455	0.005
L_3	1.655	0.005
L_4	1.566	0.005
Hallway	32.025	0.105

TABLE I: Breakdown of the length segments. L_1 is the laser to mirror, L_2 mirror to lower periscope, L_3 lower periscope to upper periscope, L_4 receiving mirror to upper hallway mirror, and the Hallway distance.

While we found the manufacturer's measurement of the focal length f, to verify its value for the lab experiment we placed the telescope at one end of the hallway and placed an object of known height h_o at a distance S_o, in which the latter was measured using the same method for the Hallway measurement in Table I. We then measured the image height S_i for the calculation of f. We recorded three trials.

Apart from the f measurement process, all data collection occurred in a dark room to ensure minimum interference with the reflected lasers. The data, which was reduced into a .csv file and consisting of $\Delta\omega$ and Δd data for day 1 (10 trials) and day 2 (4 trials) and h_i and h_o, was then exported to Python for analysis.

IV. OBSERVATIONS AND ANALYSIS

We first sought the focal length f and its uncertainty as both values are necessary for the calculation of c and its uncertainty.

For the uncertainty component u_f, we used the following propagation formula,

$$u_f = \sqrt{u_{h_i}^2 \frac{\partial f}{\partial h_i}^2 + u_{h_o}^2 \frac{\partial f}{\partial h_o}^2 + u_{S_o}^2 \frac{\partial f}{\partial S_o}^2}. \tag{4}$$

A few important notes, however, are to be made for the uncertainty u for each component. First is for u_{h_i}, in which h_i was measured using the telescope. Because the telescope dial did not have high precision markings, we assumed that the uncertainty was 10% of the measurement of h_i to account for possible small inaccuracies during data collection. For u_{h_o}, we used the same measuring tool for recording L_1 to L_4 (see Table I), thus $u_{h_o} = 0.005m$. Furthermore, for u_{S_o}, the same method of determining the uncertainty for the Hallway measurement in Table I was chosen.

While a weighted average across the f value and the corresponding u values would have been appropriate, because our lab data for f had the exact same values for h_i, h_o, and S_o, we chose not to do a weighted average and report the final value of the focal length f and u to be

$$f = (0.43 \pm 0.05)m.$$

To further ensure the accurateness of our f value, we compared it to the value of $f_{actual} = 0.445m$[4], in which we obtained a percent error value of 3.37%.

For c, we resorted to solving separately for day 1 and day 2, as we hypothesized that increasing the distance L traveled by light, accounting for that between the mirrors and that for the hallway, would affect the uncertainty value. Regarding the uncertainty value u_c, we devised the following formula,

$$u_c = \sqrt{u_{L_m}^2 \frac{\partial c}{\partial L_m}^2 + u_{L_h}^2 \frac{\partial c}{\partial L_h}^2 + u_f^2 \frac{\partial c}{\partial f}^2 + u_{\Delta\omega}^2 \frac{\partial c}{\partial \Delta\omega}^2 + u_{\Delta d}^2 \frac{\partial c}{\partial \Delta d}^2} \tag{5}$$

whereby L_m is the distance between the reflective mirrors (L_1 to L_4 in Table I), L_h the distance of the hallway,

f the focal length, ω the frequency, and d the displacement observed in the telescope. Note that for u_{L_m} and u_{L_h}, the same technique for the Hallway measurement in Table I, was used. Furthermore, for $\Delta\omega$ and Δd, we assumed the uncertainty to be 10% of the measurement, which were done for two reasons. First, the frequency reading during the experiment continued to fluctuate, but within some range of 10% of a value. Second, the small incremental reading within the telescope for the change of the light's positioning had some uncertainty; the idea for the uncertainty for h_i applies here.

Following this process, we report the value of c and the associated u for day 1 and day 2 as

$$c_{day\ 1} = (3.3 \pm 0.2)\text{E8 m/s}$$

$$c_{day\ 2} = (3.0 \pm 0.3)\text{E8 m/s}$$

We now consider the weighted average between the two for the final presented value of c and the uncertainty u as

$$c_{final} = (3.2 \pm 0.2)\text{E8 m/s}$$

Comparing this value to the value accepted by the scientific community $c = 299792458$ m/s,[2] we find a percent error of

$$\text{Percent error} = 6.0\%.$$

Our results, however, must be placed in the context of certain assumptions made for this lab experiment.

First, for the uncertainty of the hallway measurement, which was a sum of the individual uncertainties of the floor tile measurements, depend on the assumption that all the floor tiles are consistent. We argue this assumption is reasonable considering that most floor tiles were identical, but small differences could introduce additional uncertainty, which would further affect the calculations for both the focal length and speed of light measurements.

Second, considering the limit of the preciseness of the readings on both the telescope dial as well as the increments within the telescope, as well as the lack of clarity on where exactly the increment is meant to lie for the image height measurement (i.e., for f), we argue that the 10% uncertainty assumption accounts well for the fluctuations in measurements that could have occurred.

Third, we had to estimate where exactly the light ended as to move the measuring line accordingly within the telescope. This was particularly challenging as we increased the length of the hallway as the light became fainter. We contend that the 10% assumption accounts for this problem, as the observer is unlikely to be able to make a consistent error in defining a specific point in the light reading.

In light of these uncertainties, we also present an error bar graph for Days 1 and 2 below in Figure 3.

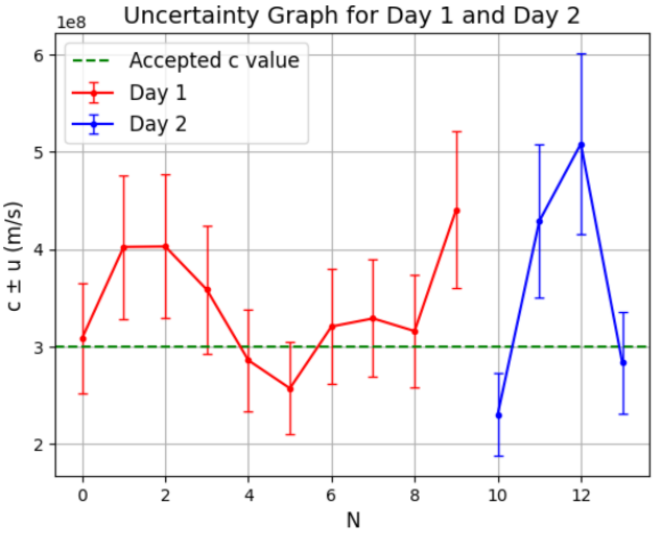

FIG. 3: Error Bar Graph for Days 1 and 2. Each individual point for each day has the respective uncertainty value of the day assigned for it.

Figure 3 above supports the previous conjecture that the distance the light travels affects the uncertainty of the measured value of c, in which for day 1 was (3.3 ± 0.2)E8 m/s and for day 2 was (3.0 ± 0.3)E8 m/s. Aside from the larger uncertainty value for day 2, Figure 3 distinctly shows the higher sporadicity of the data from day 2 compared to that of day 1. That is, there are more values that are within the uncertainty of the neighboring points for day 1, showing higher precision compared to those of day 1, in which there is visibly less precision. Considering that higher L led to a dimmer, less focused laser beam, as well as potential hindrances from the traveling medium, the higher uncertainty for day 2 is justified. Additionally, the Figure also shows the effect of the number of sample size N on how well the sample represents the true value of c. While the method of uncertainty analysis was propagation-based, which explores the individual variables and their effects on the overall evaluation of c, the Figure still offers a valuable insight on how N can affect the precision of the data.

V. CONCLUSIONS AND OUTLOOK

In this lab experiment, we offered a measurement of the speed of light c using a rotating mirror setup with varying distance L traveled by a laser beam, which came out to be (3.2 ± 0.2)E8 m/s. Compared to the accepted value of $c = 299792458$ m/s, we had a percent error of 6.0%, which reflects that our final presented value is very accurate compared to the actual value. While this small error is satisfactory, we use this as a beginning point on future methods of improvement.

First, we can address the variability in the frequency reading for the rotating mirror. As we are given that the ω of the rotating component reacts as a function of voltage (controlled by the control knob), we suspect that a mechanical component may be causing the inconsistent. By controlling for this in the future, we could reduce the uncertainty present in the $\Delta\omega$ readings.

Second, we can improve the uncertainty in the reading of the light displacement Δd by adding in a post-production step. For example, we could first take a picture of the light at some initial ω_i and then another at some final ω_f. By overlaying one over the other, adding a scale, and adding contrast in post-production, we could greatly reduce the component of subjectively guessing where the light lies.

Third, we can improve the measurement of the distance L traveled by light. Because we measured the lengths using a measuring tape or a ruler, it often involved standing in between mirrors, which negatively affected both the accuracy and precision of the readings. Furthermore, for the measurements of the hallway, because we assumed each block in the hallway was exactly identical, our measurement is susceptible to error. We can mitigate these uncertainties by a laser distance measurer. This would improve both the accuracy and precision of the L recordings.

Implementing these changes could tackle some of the uncertainties present in the methodology. However, we must recognize certain systematic sources of error. First, because the medium that light travels is not a vacuum, it is susceptible to error from humidity, temperature, and other particles in the air. Second, the surface of the reflective mirrors, which may not be perfectly reflective, may cause light to be less focused, as was indeed observed in the lab experiment, and affect the small displacement recorded in the telescope. While we suspect these will not be a significant cause of uncertainty, they are nonetheless factors that should be accounted.

Acknowledgments

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