Using a Laser to Measure the Speed of Electromagnetic Radiation

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(Dated: February 2, 2024)

The speed of light seems instantaneous to our eyes however, taking a closer look, we observe that is not the case. In our preliminary findings, we observe that the speed of light is finite and is dependent on the frequency of the light. We used a 1 mW laser that expels light at a wavelength 600 - 700 nm to measure the speed of light. At 0.5 MHz input, the speed is $2.208 \times 10^7 \pm 2.11 \times 10^6$ m/s. For 1 MHZ, $2.688{\times}10^7 \pm 1.85{\times}10^6$ m/s. We find that our observations do not match the current agreed speed. We find that our measurements are magnitude off and more than 1 σ away from the theoretical value of 299,792,458 m/s.

I. INTRODUCTION

The way we make observations of the world can first be done by the eye. What our eyes observe is a form of electromagnetic radiation (commonly known as light). Our eyes do not have the ability to observe the time that it takes for light to reach our eyes from a source. People such as famous French philosopher René Descartes believed that the speed of light is observed to be instantaneous [1]. Descartes strongly believed that his observations were correct so much so that he was willing to reduce the credibility of all his other philosophical writings. He tried to find a delay of the light when the Earth covers the Moon. The largest flaw in his experiment is that the distance between the Earth and the Moon is far too small to detect any delay with contemporary instruments.

The first to measure and determine that the speed of light was not infinite was done by Danish astronomer, Ole Roemer. While trying the study Jupiter's satellites and their motions he noticed that their expected eclipses were off by almost 10 minutes. After a scholarly discussion with Giovanni Domenico Cassini, Roemer determined that light indeed has a finite speed [1]. Now in the present time, the most accurate measurement of the speed of light was determined to be 299,792,458 m/s [2]. This is theorized to be the speed limit for matter by special relativity. Einstein determined that the speed of light remains the same in any reference point that it is measured in.[3]. In this experiment, we will attempt to come up with a measured velocity of the speed of light by use of the classical equation:

$$v = \frac{\Delta d}{\Delta t}$$

where Δd is the change in the measured distance and Δt is the change in time.

II. METHODOLOGY

Just like Descartes, we hoped to measure the speed of light by finding a delay in the wave signal produced by the Universal Signal Receiver. We hoped to find the delay between a wave that is consistent and the produced wave signal.

Due to the precision of our instruments (See Figure 1), having the most amount of distance separation was the best way to reduce the uncertainty on the delay. The best option was to use the Mallot basement hallway due to its long distance and since it is on the ground floor, the building will have less vibrations which will make the alignment process a lot more seamless. Another reason we chose that hallway was due to the lack of traffic of people. Although the laser is graded to be grade 1, it is still best to keep safety a priority.

The point of reference is important to measure as accurately as possible. Our zero-point started at the spot where the laser exits the apparatus. To keep our results as accurate as possible, we aligned our photo receiver as closely to the zero point by eyeball. We used a 24' measuring tape to measure the distance to the mirror. We placed tape on the floor next to the mirror to indicate different distances. The distances we arbitrarily decided on were 352 in, 882 in, and 1570 in. To compare with the theoretical speed, we converted them to meters. We must also keep in mind that Δd includes the total distance, so theoretically, we just multiply the distance to the mirror twice since the light is being reflected to point 0. One concern that must be addressed is the angular separation between the laser and the receiver. Due to physical limitations, we cannot place the receiver in the same location as when the laser is expelled. This means that there is a small distance in addition to the measured distance to the mirror. We ultimately decided that this separation may account for intentionally less than an inch making it negligible.

Next, we needed a way to measure the delay. We chose to do that by using an oscilloscope. The oscilloscope will measure a reference wave and the observed signal from the receiver. To generate a reference wave, we used a function generator. This function generator will simulate a sinusoidal wave.

$$y = A\sin(\omega t + \phi)$$

We were testing to see if there is a difference in the speed of light between the different frequencies. We ultimately decided to use 0.5 MHz, 1 MHz, 4 MHz, and 6.7 MHz. We had to adapt the settings of the function generator in order to get "good" data. At 352 in, we used a peak-to-peak voltage of 5 V. At the other 2 distances, we used a 10 V peak-to-peak in order to better concentrate the light. In addition to that voltage increase, we use a lens to refocus the light since at larger distances, the light was dispersed which made it too faint for the receiver to make a proper reading. The lens was held by hand close around 1 inch away from the receiver. We repeated this measurement at each distance recording the delay.

The oscilloscope was set to receive two signals. The first was from the function generator and the second was from the receiver. The function generator's simulated wave was set in channel 2 and was decided to be the reference wave and the receiver signal was inputted into channel 1. We then measured the delay as measured from channel 2 in reference to channel 1.

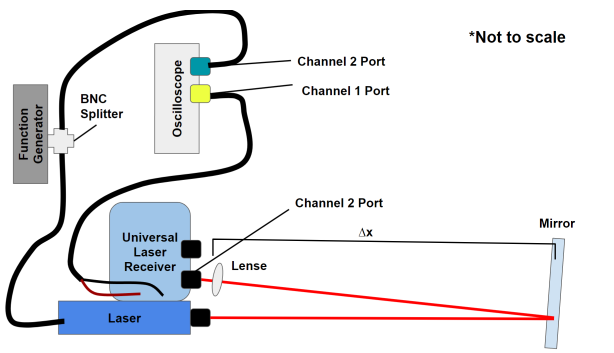

FIG. 1. The Agilent 33220A 20MHz function generator is the first part of our instrument setup. The BNC splitter connected to the function generator splits the output signal into two different paths. One part of the signal is sent directly to be measured by the 70 MHz oscilloscope in the channel 2 port. The laser receives the simulated wave function, specifically the frequency, and is powered by 1 mW. The light expelled is in the 600 - 700 nm range. This incident light is then reflected by a mirror and aimed at the receiver. At larger distances, a lens was used to focus the dispersed light due to reflection. The receiver detects the photons and sends a signal for the oscilloscope to read in channel 1.

III. RESULTS

We found that the speed of light was dependent on frequencies and neither measured frequency is the theoretical 299,792,458 m/s. We only were able to get enough measurements at the 0.5 MHz and 1 MHz frequencies. We noticed that at higher frequencies, it was almost too noisy to tell whether a measurement could clearly be determined as a signal or just noise. This is due to environmental interference and the quality of the wires causing noise.

At 0.5 MHz, the calculated speed is determined to be $2.208 \times 10^7 \pm 2.11 \times 10^6$ m/s. For 1 MHZ, $2.688\times10^7\pm 1.85\times10^6$ m/s.

In Figure 2, you can see that the points are plotted. Using Python, we created a linear fit (y = mx + b) to find the slope equation. We found that the inverse of the slope (m) is our measured speed of light. For 0.5 MHz, we got the equation $3.72 \times 10^{-08}x + -9.11 \times 10^{-07}$. For 1 MHz, we got the equation $4.53 \times 10^{-8}x - 1.13 \times 10^{-6}$. Since the oscilloscope measures the delay of sinusoidal signals, it is determined that the delay may be off by periods. The delay then needs to be adjusted so that Δ d is measured in the same period.

A. Uncertainties

Our largest uncertainty was determined to be statistical uncertainty. The precision was sufficient for the range in the distance. However, the largest issue physically was that we had to hold up the lens and the universal laser receiver due to angular separation when the laser was reflected. It was difficult to keep the light aligned but we ran those trials multiple times in order to see if the delay magnitude was in the appropriate magnitude.

We claim that statistical uncertainty is the largest specifically because when calculating the propagated error on the measurements, statistical uncertainty is the largest.

For numerical uncertainties, we claim that the delay measurement had an uncertainty of ± 0.5 ns. This was the smallest measurement that the oscilloscope could measure. The distance measuring tape has an uncertainty of 1 inch. One uncertainty that we were careful to claim as negligible was the uncertainty between the oscilloscope since the measured frequency was similar and would be small compared to the large magnitude of the frequencies. We also determined that the uncertainty of the coax cables was also negligible for the same reason.

IV. CONCLUSION

Our data conclusively shows that the speed of light does not match the theoretical 299,792,458 m/s. Our measurements are almost an entire magnitude off from the theoretical speed. Our error is not large enough to allow our results to fall within the theoretical value within 1 σ. We do have a more accurate value of the speed of light compared to Descartes. This means that we found that the speed of light is not finite. While looking for where we can improve our results, we looked at the index of refraction. However, we found that the index of refraction will not have a large enough effect on the speed to help us reach the threshold.

A. Future Data Collection

We hope to take better data in the near future in the same conditions. However, there will be a few changes. Firstly, we will use the lens at shorter distances. We did not think of the idea at first because the light was not dispersed at a shorter distance. We also plan on changing the frequencies we use to avoid environmental noise as much as possible. We also plan on working on our cable management as the oscilloscope can pick up some of the signal that does not come from the coax cables. We also plan on attempting to have a more stable way to hold up the lens as our hands cannot hold it perfectly still. The oscillating motions of our hands made it difficult for the oscilloscope to get accurate readings.

For the sake of the argument, we can also make more unrealistic improvements. We hope that we can get an oscilloscope with a more accurate clock. We could also check the clock on the oscilloscope with another one of the same kind with another splitter however, this might make the signal more noisy because the BNC adapter is not that good in quality. We also hope to do it in a secluded area where there are no external signals to interfere with the measured signals.

[1] A. Einstein, Zur elektrodynamik bewegter körper, Annalen der Physik **322**, 891 (1905), https://onlinelibrary.wiley.com/doi/pdf/10.1002/andp.19053221004.

[2] A. Chapman, The accuracy of angular measuring instruments used in astronomy between 1500 and 1850, Journal for the History of Astronomy **14**, 133 (1983).

[3] D. Newell and E. Tiesinga, EnglishThe international system of units (si), 2019 edition (2019).

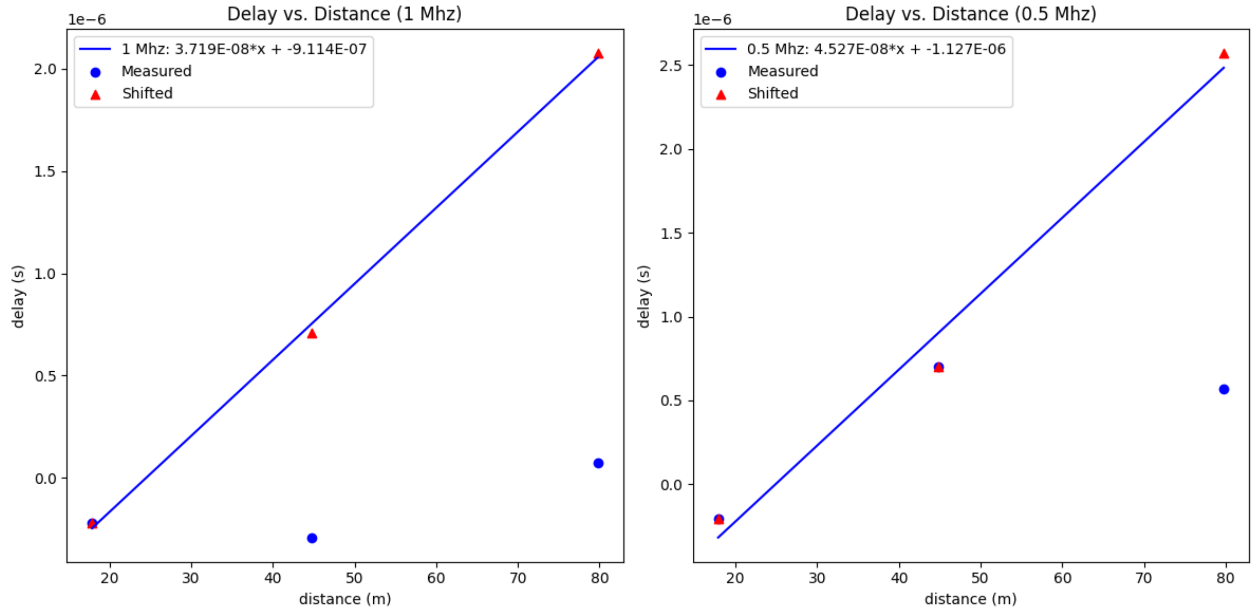

FIG. 2. These are the plotted results of 1 Mhz and 0.5 Mhz. The blue dots are the raw data where the delay is not shifted by a period. We adjusted them by adding multiples of the period which are represented by the red triangles. The delays are in seconds to make it easier to see the difference between each distance. Without any residual value or χ^2 value, we observe that our data was close to our trend line.