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Speed of Light

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Abstract

We evaluated the speed of light using the Faucault method. We passed the beam of light through the rotary mirror and reflected it back to the source. We determined the speed of the rotary mirror by measuring its frequency and measured corresponding shift of the light beam form its initial path. We ploted our measurments and determined that the speed of light is $(2.18\pm0.10)\cdot10^8$ m/s. This result is 27.3% different form the accepted value.

Itroduction

Background:

When we want to measure the speed of something, we usually measure the distance, and time it takes to travel that distance. From these measurments we can calculate the speed. The speed of light is so fast, that in theory nothing can travel as fast as the speed of light. It is so fast that only in 17th century scienecists proved that light does not travel instanteneously. Measuring such a fast speed by the usual methods would be almost impossible and we would get a huge uncertanty. However, the speed of light is a constant of nature that is incredibly important, so sciencists were thinking of different techniques to measure the speed of light as precise as possible.

One of the fisrt attemts to measure the speed of light belongs to Galileo. He used two shuttered lanterns that are a mile apart. First person opens the lantern; when on the other side second person sees the lights he opens his lanterns, so the first person can also see the light. Galileo would measure the time between the first person opened his lantern and saw the light from the other side, to calculate the speed of light. Unfortunately, this technique was not good enough to get good results, mainly because human reaction times give a very big uncertainty [1].

The first successful measurement was made by Ole Roemer, who was studied Jupiter moons orbits. His result was 214,000 km/s [2]. The first direct measurement belongs to Louis Fizeau, who send the light through the rapidly rotating toothed wheel and then the light reflected back from the mirror [1].

Leon Foucault improved Fizeau experiment by replacing the toothed wheel by the rotary mirror. The light travels to the rotary mirror and then travels to the regular mirror that is places at some distance away. Then the light reflects back to the rotary mirror. By the time the light went from the rotary mirror to the regular mirror and back, the rotary mirror turned by a small angle. That causes the light to be reflected slightly different direction than its incident path. The faster the rotary mirror is rotating, the more the light beam is deflected from its incident path. In 1862, Foucault concluded that the speed of light is 299,796 km/s [3].

Later Albert Michelson made more improvements on the experiment and in the year of 1933 he stated that his result is 299,774 km/s [3]. Nowadays the accepted value of the speed of light is 299,792,458 m/s. [4]

Theory and equations:

For this experiment, we use the technique developed by the Fizeau and improved by Foucault and Michelson. Even though, we use the technique and experimental design developed many years ago, we use modern equipment to make the measurements easier. For example, we use the laser instead of the lamp as a light source because laser is a more concentrated beam of light and it is easier to determine the small displacements with it. We also use the lens to make sure that the beam stays converged when it hits the rotary mirror on its way back.

If we know all the distances in our setup, we can find time that elapses while the beam travels certain distance. We cannot measure this time but we can express it in the equation and use in our further calculations. Since we know the time it takes for the beam to go from the rotary mirror to the regular mirror and back, we can calculate the angle that the mirror turned during that time. When we know the angle, we can calculate the shift of the beam form its initial position. Using these relations we get the Eq.1 [5], where in order to calculate the speed of light we have to measure the speed of the of the rotary mirror and the shift of the reflected light.

$$c = 8\pi \cdot (f + 2a) f \cdot \frac{\nu}{\Delta x} \tag{1}$$

In Eq.1 f is the focal length of the lens and a is the distance from laser to the rotary mirror. We setup our experiment so the distance from rotary mirror to the regular mirror is the same as from the laser to the rotary mirror. I introduce the parameter b – the distance form lens to the regular mirror. Therefore, we can use relation in Eq.2 [5].

$$a = f + b \tag{2}$$

For the distance a we can choose any arbitrary value. However, we want to be smart when we choose the distance a, because on the big distances laser loses its intensity due to divergence, so we would not get a good reflected picture. To calculate the optimal value for a and corresponding value for b for the specific lens we use the relation from Eq.2 and the law of imaginary that is represented by Eq.3 [4].

$$\frac{1}{f} = \frac{1}{b} + \frac{1}{a + f} \tag{3}$$

Since we cannot directly measure the speed of the rotary mirror, we measure the frequency of the rotations and from that frequency we can calculate the speed.

To determine the speed of light from the gathered data, we used plotting method. I rearranged Eq.1 so I can plot shift versus speed and do linear fit with the slope directly related to the speed of light. From that slope, I calculate the speed of light.

Procedure

Equipment and setup:

As it was mentioned in the introduction, for this experiment we used modern equipment comparing to what Michelson or Foucault used. For the light source, we used Intelite green diode-pumped solid-state 5mW laser. We used Leybold 47640 rotary mirror, and Leybold 52140 variable transformer to change the speed of the rotary mirror. For the optics we used front silvered mirror, f=500 cm lens and beam splitter. All the optics were set on the V-shaped stand bases. The purpose of the beam splitter is to reflect half of the beam to the wall, where measuring the shift of the beam is much easier than on the surface of the laser casing. The setup is shown in Figure 1, where distances are labeled with corresponding letters (I used them to discuss equations in introduction).

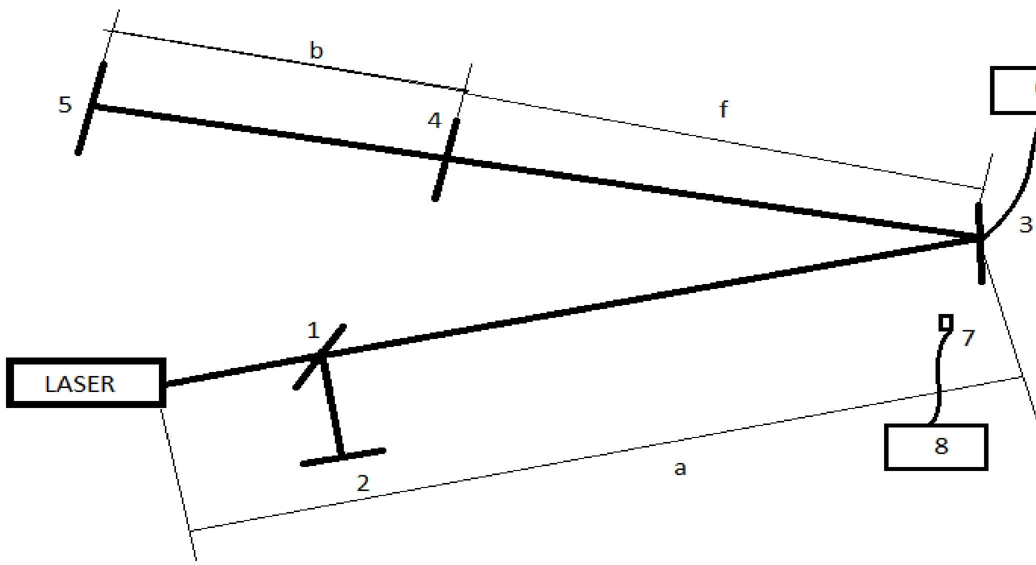

Figure 1: The setup for the experiment, where we can see how the beam travels through optics. 1-beam splitter, 2-the wall (piece of paper, where we mark the shifts), 3-rotary mirror, 4-lens, 5-regular mirror, 6-variable transformer, 7-simiconductor detector, 8-oscilloscope.

We had to make sure that the laser is set parallel to the ground, so the light beam always goes parallel to the ground. Rotary mirror and optics were set on the cardboards to prevent possible movement of the light form the motor vibrations. While doing setup, we used the wrench to manually rotate the rotary mirror. When setting optics, we made the beam go right through the center of the optics, and optics were set perpendicular to the light, to decrease the uncertainty of the measurements. We adjusted the regular mirror to make the reflected beam go to the same spot in the lens where it leaves the lens, so the reflected beam travels the same path back. The distances for the setup are determined by the equations that were discussed in the introduction.

To measure the frequency of the rotary mirror we used the semiconductor detector connected by the BNC cable to the Tektronix TDS1002B digital oscilloscope. Semiconductor detector converts light into voltage, which can be measured by the oscilloscope. From the oscilloscope-measured frequency, we can calculate the speed of the rotary mirror. In order to make oscilloscope display the frequency measurement I had to set the following settings: AC coupling (change in CH1 menu), slope – falling (change in TRIG menu), use "set to 50%" button to set the trigger level, type of measurement – frequency (use "measure" button to change). Oscilloscope also shows the graph of voltage versus time, where voltage spikes occur when the beam crosses the semiconductor detector. We had to find the optimal position for the semiconductor detector to make the output signal to be the greatest possible we can get.

Preforming the experiment:

First, we had to mark our initial position line on the wall. We used the wrench to turn the rotary mirror so that reflecting beam goes through the center of lens. On the wall, we observed the green dot from the laser – that was our reflected beam. My partner marked the dot as the initial position. I powered the variable transformer and started to slowly increase the voltage.

As I increase the voltage, the dot on the wall shifts from the initial position. When my partner saw a shift big enough, so he can mark the line for it, he told me to stop. My partner marks position "one", and my other partner writes down the frequency that is measured by the oscilloscope for this specific position. We kept increasing the voltage and taking data until we reached about 50V. If I kept increasing the voltage above the 50V, there beam did not shift anymore. Since the shift is very small, we only got four measurements, so we did a second trial to have more data. After doing trial one we found some misalignments in our setup, that we fixed before doing trial 2. After doing both trials, we measured with caliper the shifts form the initial position for each measurement.

Results

We gathered data for the rotary mirror rotational frequency – f, and the shift of reflected beam – Δx. The frequency readings on the oscilloscope were not very stable, so we recorded an appropriate uncertainty for each measurement. Uncertainties for the frequencies are in order of 0.5-1 %. The shift is very small, but we used a caliper for measuring. We reported the uncertainty for the shift according to the caliper smaller divisions, which gave us uncertainty in order of 0.2-0.3%.

Since Eq.1 depends on the velocity of the rotary mirror, I had to convert the frequency to the velocity. Velocity equals to the distance over time. One rotation is 2π distance and time elapsed is just the period of the rotation. Period is just one over frequency. The rotary mirror we used in our experiment is double sided, so the peaks on the oscilloscope represent half of the rotation instead of the full rotation. Therefore, the actual frequency of the rotary mirror is twice smaller than the measured frequency. From these relations I get Eq.4 to calculate rotary mirror's speed.

$$v = \pi f \tag{4}$$

The Eq.1 shows how to express the speed of light in terms of constants and measured variables. To get the best result for the speed of light we want to plot the data and do linear fit, so we can determine the speed of light from the slope. In order to do so, I had to rearranche Eq.1 to get Eq.5 [5], where plotting 1/Δx vs 1/v should give the slope that is directaly related to he speed of light.

$$\frac{1}{\Delta x} = \frac{c}{8\pi \cdot (f + 2a) f} \cdot \frac{1}{v} \tag{6}$$

I did the plots for both trials and it turned out that the data for the first trial was very inconsistent. The small missalignmets that we had affected the uncertanty a lot.Therefore, I decited that doing calculations only with the data from the second trial would give me the best result. The graph of the second trial is represented in Figure 2. In the legend I recorded the slope of the linear fir for the data with its uncertanty. On the graph we can observe how good the data fits the line. Therefore, I know we got consistent results for the second trial.

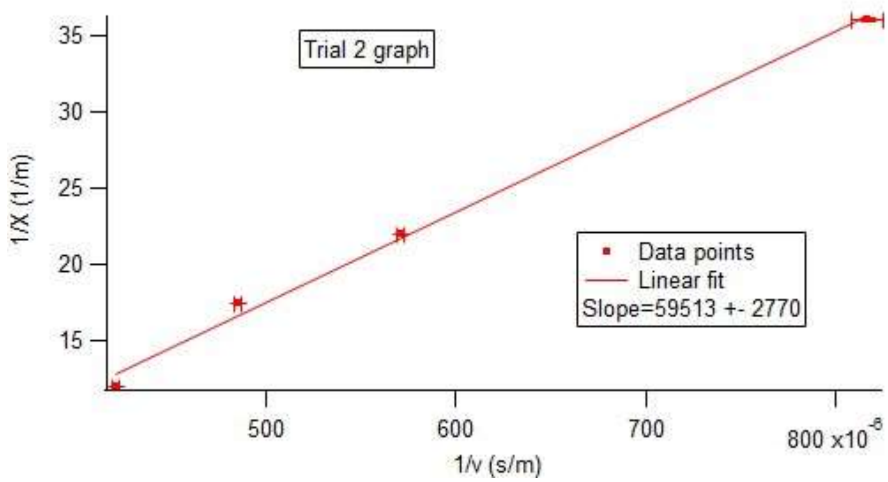

Figure 2: The graph of 1/Δx vs 1/v for the second trial data.

From Eq.6 we see that the slope of the graph is the speed of light multiplied by the costants. It is given to us that the lens we used has focal lengh 500 cm. The calculated value of distance a for my setup is 1207.12 cm. Using thise nummber I calculate the value of the constant that the speed of light is multiplies with. My constant is 3662.142. Therefore the value I get for the speed of light is $c=(2.18\pm0.10)\cdot10^{8}$ m/s. Comparing my value with the accepted value of c=299,792,458 m/s [3] gives the disperancy of 27.3%.

The desperancy is pretty big, however, there are multiple factors that may affected my result. The accepted value for the speed of light is measured in vacuum. We measured the speed of light in air. In addition, the beames passed through a lot of optics. Those factors may have slowed down our light a little bit. Also, the beam did not perfectly converged on the wall, it was about 2 cm in diameter, and the shift was very small. Therefore if was harder to mark the shift lines and any small error has a big effect on the results. However our data is very consistent, so I assume we do not have a lot of error form measuring the shift. Even though this experiment is made on a big scale, any small missalignmets may have afacted the precision of our data. Since we alligned most of the setup by just looking at it, we may have some missaligments that affected our result and gave such a big despirancy.

Conclusion

The relationship between the speed of light and the measured quantities Δx and frequency are represented in Eq. 1 or Eq.6. I used the linear fit method to find the speed of light. My data fit the linear fit very well. The value I got for the speed of light is $c=(2.18\pm0.10)\cdot10^8$ m/s. My value differs from the accepted value by 27.3%. Some of the error comes from the fact did we did our measurments not in vaacum but in air and the light passed through a lot of different optics. Also, because the speed of light is so big, any small misalignments in the experiment have a big effect on the result. Therefore, most of our error comes from the small misallignmets in the setup. In adition, we did not have a lot of data, becasue the first trial was not succesfull, so I did not use it for calculations. Having more data would improve the result.

References

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