Re-Discovering the Speed of Light

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Abstract: In this experiment we measured the speed of light using Foucault's method. This method is from the 1850s. This experiment led to Einstein's theory of relativity and other important theories due to the speed of light constant. We measured the speed of light by reflecting a laser off of a rotating mirror. We get the speed of light by measuring the change in position of the point image. We got 1.808×10^8 m/s ($\sigma \pm 2.7 \times 10^6$) for our speed of light. Our percent error is 39%. Our data is a little off, but this is due to the number of variables there are in this experiment. We need to find a better way to measure our variables more carefully and precisely. Then our numbers should be in agreement with others work.

Introduction: Light is one of the most important natural phenomena in nature. Light was thought to have infinite speed until the 17th century. The speed of light always has the same speed to the observer, whether it comes from the sun, a light bulb, or a laser. Historians credited Galileo as the first scientist to try to determine the speed of light. In order to do this He had his assistant stand at least one mile away from him. They both had lamps which could be cover or uncovered. Galileo would uncover his lamp and the assistant would uncover his lamp as soon as he saw the light from Galileo's lamp. From the elapsed time Galileo inferred that light travels at least ten times faster than the speed of sound[1]. This was a very important first step to measuring the speed of light, because this experiment showed that the speed of light is not infinite. From this scientists determined you need a very long distance to measure something that moves at extremely high speeds. Multiple other scientists tried to determine the speed of light.

Fizeau tried it in 1849. Fizeau developed a brake through method for measuring light. He measured the speed of light by shining light between a rotating cogwheel. The wheel rotated hundreds of times a second. It was therefore possible to measure the speed of light. He spun the cogwheel faster and faster until light could not go through the gap to the remote mirror, and then back through the same gap. From this he was able to get the time, and how far the light traveled. Using this information he measured the speed of light to be $3.15*10^8$ m/sec. A short time later Foucault used a similar method to measure light using a rotating mirror instead of the cogwheel. This will be them method we use to get our results. He was able to measure light velocity to be 2.99774×10^8 m/sec. The current accepted value for the speed of light is 2.99792458×10^8m/sec.

These scientist and others established the procedure of how to measure light, without these scientists we would still think the speed of light is infinite. Finding the speed of light has led to some significant ideas and discoveries in science. Knowing the speed of light has given us the ability to determine the distance from earth to the stars, planets within our galaxy and even some outside our galaxy[2]. Speed of light has allowed us to determine the index of refraction[3]. Possibly the most important theory that was derived from knowing the speed of light is Einstein's theory of relativity[4]. That is why the speed of light constant is one of the most fundamental and important constants in physics and of upmost importance to measure it accurately and precisely.

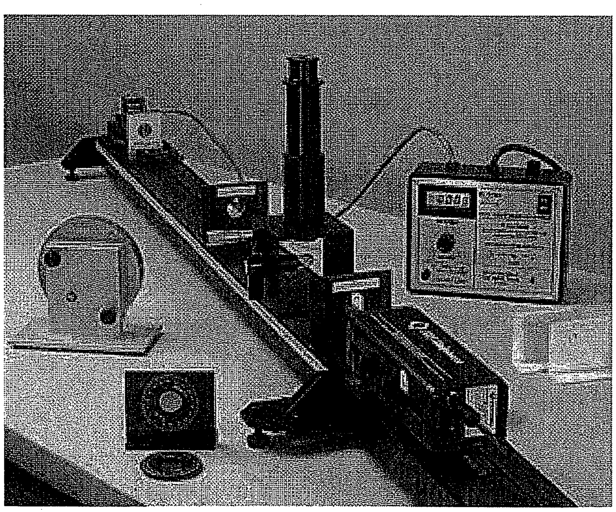

Figure 1 Pasco Scientific Speed of Light Apparatus[5]

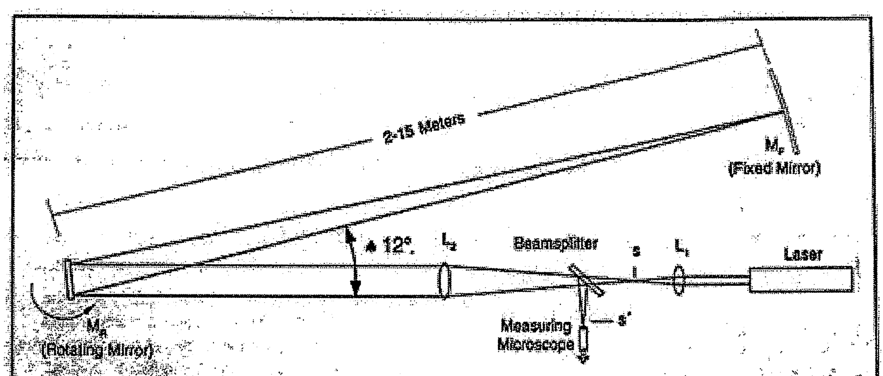

Figure 2 Diagram of Foucault Method[5]

Method: We used the Pasco Scientific Speed of Light Apparatus to measure the speed of light, show in figure 1 and the set up used in figure 2 above. Once everything was aligned we saw a focused point image through the measuring microscope. The point image looked like a bright dot with some interference fringes around it. The apparatus optic path goes as follows; the laser goes through lens one. After it goes through lens one it goes through the beam splitter. Then it goes through lens two and then hits the rotating mirror. After it hits the rotating mirror it reflects off of it as it is spinning to hit the fixed mirror. The fixed mirror is at approximately 12° angle away from the incident beam of light. The light then reflects off the fixed mirror and travels back to hit the rotating mirror. The laser beam then reflects back off the rotating mirror towards the laser on its original path. We measured the distant of lens one (L_1), lens two (L_2), and the rotating mirror (M_R) from the end of the optics bench. We also recorded how far the fixed mirror (M_F) was from the rotating mirror (M_r). The displacement of the point image from the cross hairs in the microscope was another thing we measured. While measuring the displacement of the point image we also measured the rotation velocity of the mirror (M_R). We measure the displacement and the velocity each time we alternate our rotation from clockwise to counter clockwise.

Theory: In order to get to our finished equation that was used in Foucault's method to measure the speed of light, it is necessary to determine how speed of light and the displacement of the image point are connected together. The rate of rotation of the rotating mirror, distance from the fixed mirror to the rotating mirror and the magnification of lens one and the distance between lenses one, two and the fixed mirror all affect the displacement. The laser light follows the path as described above. The light that goes from the laser to the fixed mirror to the rotating mirror is at angle θ. When the mirror is not rotating the angle of incidence of the light path as it strikes the rotating mirror is also θ. Since both angles are equal between the incident and reflected rays the angle become 2θ. When the mirror is rotating you can think of the laser as pulsing light. This makes the pulse of the laser at a slightly later time, when the rotating mirror is at an angle $\theta_1 = \theta + \Delta\theta$. The angle of incidence is now equal to $\theta_1 = \theta + \Delta\theta$. This makes the total angle $2\theta_1 = 2(\theta + \Delta\theta)$. We now define the point strikes the fixed mirror as S_1. We also define D as the distance between the fixed mirror and the rotating mirror. From this we can get the difference between S and S_1. The equation for this is $S_i - S = D(2\theta_1 - 2\theta) = D[2(\theta + \Delta\theta) - 2\theta] = 2D\Delta\theta$ (Equation 1). Since the rotating mirror makes the light leaving the laser work like a quick pulse of light we can think of it this way. There is a pulse of light and it strikes the rotating mirror when it is at some angle. We will call it θ for now. By the time the pulse of light makes it back from the rotating mirror the mirror will be at a different angle. We call this angle θ_1. If the mirror wouldn't have been turning the point image would have refocused of s. Since the rotating mirror is at is now at a different angle, this causes a change in s. Knowing the critical geometry of virtual images is the same as for reflected images we can look at this as a virtual image problems[6]. Using this we can use our basic optics $\frac{H_i}{H_0} = \frac{d_i}{d_0} = \frac{i}{0}$, $H_i = \Delta s, H_0 = \Delta S$. Using those two equation we get $\frac{\Delta s}{\Delta S} = \frac{i}{o}$, so$\Delta s = \frac{i}{o}\Delta S$. We can write an expression for the displacement (ΔS) $\Delta S' = \Delta s = (i/o)\Delta S = \frac{A}{D+B}\Delta S$ (Equation 2). Combining equation 1 and 2 and substituting in $\Delta S = S_1 - S$. This formula relates to the initial and secondary positions of the rotating mirror[8]. The formula for this is$\Delta S' = \frac{2DA\Delta\theta}{D+B}$ (Equation 3). The angle Δ θ depends on the rotational velocity of the rotating mirror and the time the light pulse takes to travel between the fixed and the rotating mirror. The equation for this is $\Delta\theta = \frac{1Dw}{c}$ (Equation 4). C is the speed of light. The rotational velocity is w. The unit for w is radians per second. We then use equation 4 to replace Δθ in equation 3 to get: $\Delta S' = \frac{4AD^2w}{C(D+B)}$ (Equation 5). With a little rearranging we get the equation for the speed of light. $c = \frac{4AD^2w}{\Delta S'(D+B)}$ (Equation 6). C is equal to the speed of light. W is equal to the rotational velocity of the rotating mirror. The distance between lens two and lens one, minus the focal length of lens two gives us A. B is equal to the distance between lens two and the rotating mirror. The distance between the fixed mirror and the rotating mirror is D. ΔS' is equal to the displacement of the image point as viewed through the microscope. We adjusted our equation for our experiment to get the final form of the equation that we will be using:

$$c = \frac{4AD^2(\frac{Rev}{sec_{cw}} + \frac{Rev}{sec_{ccw}})}{(D+B)(S'_{cw} - S'_{ccw})}$$ (Equation 7)[7]

Data and Analysis: Our measurement for A was .262 m. We got a by finding the distance between lens two and lens one minus the focal length of lens one. B is found by measuring the distance between lens two and the rotating mirror. We got .492 m for B. D is the distance between the rotating mirror and the fixed mirror. B is equal to 13.2 m.

Trials	Rev/Sec cw	Scw	Rev/Sec ccw	Sccw	C
1	1003	1.1114E-02	1006	1.0175E-02	1.7919E+08
2	1018	1.1116E-02	1091	1.0171E-02	1.8692E+08
3	1016	1.1122E-02	1034	1.0179E-02	1.8207E+08
4	1018	1.1125E-02	1017	1.0178E-02	1.7998E+08
5	1045	1.1127E-02	1045	1.0168E-02	1.8253E+08
6	1010	1.1120E-02	1007	1.0173E-02	1.7838E+08
7	1024	1.1129E-02	1022	1.0170E-02	1.7869E+08
8	1019	1.1124E-02	1026	1.0176E-02	1.8067E+08
9	1006	1.1119E-02	1007	1.0171E-02	1.7784E+08
10	1031	1.1128E-02	1030	1.0180E-02	1.8208E+08

				Average	1.8084E+08

Table 1 Shows our measured values of the displacement in the point image, how fast the mirror spun and our calculated value for the speed of light.

Table one show our measured results of displacement in the point image, how fast the rotating mirror was spinning and our calculated values for the speed of light. We calculated the speed of light by plugging our numbers in to equation 7. We got 1.808×10^8 m/s (Ơ$\pm 2.7 \times 10^6$) for our speed of light. Our percent error is 39%.

Results: Our measurement for the speed of light is clearly not very close. The main problem in the quality was the number of variables in this experiment. There was also not a very good way to measure the distance from the fixed mirror to our rotating mirror. That attributes to some of our error. Our uncertainty is relatively large due to the variation in the rotating mirror speed and the point image. The point image was hard see if it was on the exactly on the center of the cross hairs in the microscope or if it was off by just a tiny bit.

Conclusion: Our results were off by a large margin. Some implications of our work, is that in further work our measurements need to be read more precisely. We also need to be very careful to check our accuracy of our measurements as well. We also need to check our alignment more often. Another suggestion for further work is to make sure there we take more time working on the lab to make sure everything is aligned and checking measurements. Another suggestion for further work would be to move the fixed mirror farther back thus improving our accuracy.

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Determination of the Speed of Light

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Until around 1600 very few scientists had begun to think about the phenomenon of light, and most thought its speed to be infinite. Through the work of Galileo, Römer, Fizeau, Foucault, Michelson, and many others, the speed of light was eventually determined to be 2.99774×10^8 meters/second. Using Foucault's method of experimentation involving a rotating mirror, a fixed mirror, and a light source, the displacement of the image produced by the light source was able to be measured. A result of $1.8084 \times 10^8 \pm 2.71 \times 10^6$ meters/second was determined, which is a 39% error in comparison to the present day velocity. Although this error is significant, it could be attributed to the number of measurements necessary to make the calculation.

Introduction

The speed of light, though today is considered to be one of the most fundamental pieces of knowledge in the scientific world, was at one point only speculated upon by a few scientists. At the time in history when only a few scientists thought about this phenomenon, most of them thought it to be infinite. However, Galileo decided that he wanted to measure it and created a method to attempt this.

Galileo's method involved two people using covered lanterns. These two people were on the top of two hills that were about a mile apart. The first person would uncover their lantern and time how much time elapsed until the second person uncovered their lantern, which was done when this person saw the first uncover their own lantern. This number was divided by twice the distance between the two people, as the distance the light traveled would have been from the first person to the second and back to the first, and the speed of light could then be determined (Reference 1).

Galileo discovered the speed of light was far too large to be determined through the procedure he developed, but this attempt opened up the field for other scientists to also attempt to measure the speed of light (Reference 1).

Olaf Römer was the first scientist to make a successful measurement of the speed of light. Römer was an astronomer and his measurement of the speed of light was based off of his observations of the eclipses of one of the moons of Jupiter. In his observations, Römer noticed that the eclipses were shorter when the Earth was moving towards Jupiter and longer when the Earth was moving away from Jupiter. This observation is attributed to the speed of light being finite. The last glimpse of the moon can be seen as the last bit of light reaches the eye, which is slightly delayed from the time the moon actually moves behind Jupiter. Römer noticed a longer delay when the Earth was moving away from Jupiter. Finally, in the year 1675, after continuing to record these observations, Römer was able to calculate the speed of light to be 2.1×10^8 m/sec (Reference 3).

Although Römer's measurement was fairly close to the modern day measurement, it was too slow due to the inability to accurately measure distances in space at the time. Enter Fizeau in 1849 who developed another method for measuring the speed of light on Earth. He setup a light source and placed a revolving cogwheel in front of it. The light was aimed at a distant mirror, and the rapidly spinning cogwheel was used to created pulses of light on the mirror. The mirror then reflected these light pulses back toward the original source. The revolving cogwheel would either block the incoming light or let it through depending on the position of the revolving wheel. Using this method, Fizeau was able to measure the rate at which the cogwheel rotated along with the distance between the cogwheel and the mirror to measure the speed of light to be 3.15×10^8 m/sec (Reference 2).

Finally, our method is based on the improvements Foucault made to Fizeau's method. Foucault replaced the rotating cogwheel with a rotating mirror. Michelson then took Foucault's method and measure the speed of light to be 2.99774×10^8 m/sec (Reference 4).

Method

The method used to carry out this experiment was very similar to the method Foucault developed based Fizeau's method, as described earlier. The light source is first aligned with the rotating mirror in its stationary position. Two lenses and a beam splitter are placed in line with the beam of light as well, as shown in Figure 1 below.

The beam of light travels through L_1, a convex lense that focuses the light at point s. L_1 had a focal length of 48 mm and was placed at the 93.0 cm mark on the optics bench. L_2, which has a 252 mm focal length, is then placed so that the image point at s is reflected at an angle from the rotating mirror (M_R) to the fixed mirror (M_F). This location is at 62.2 cm on the optics bench. The light hitting the fixed mirror is reflected back to the rotating mirror along the same path it originally traveled, and the image point is focused on point s. The beam splitter is put at the 82.0 cm mark on the optics bench and is used to view the reflected point image through the measuring microscope.

The rotating mirror rotates very rapidly, which displaces the point of reflection on the fixed mirror. With this change, the light travels from the fixed mirror back to the rotating mirror at a different angle. This displacement, or change is angle, is the main recording made and is the necessary measurement to help us determine the speed of light.

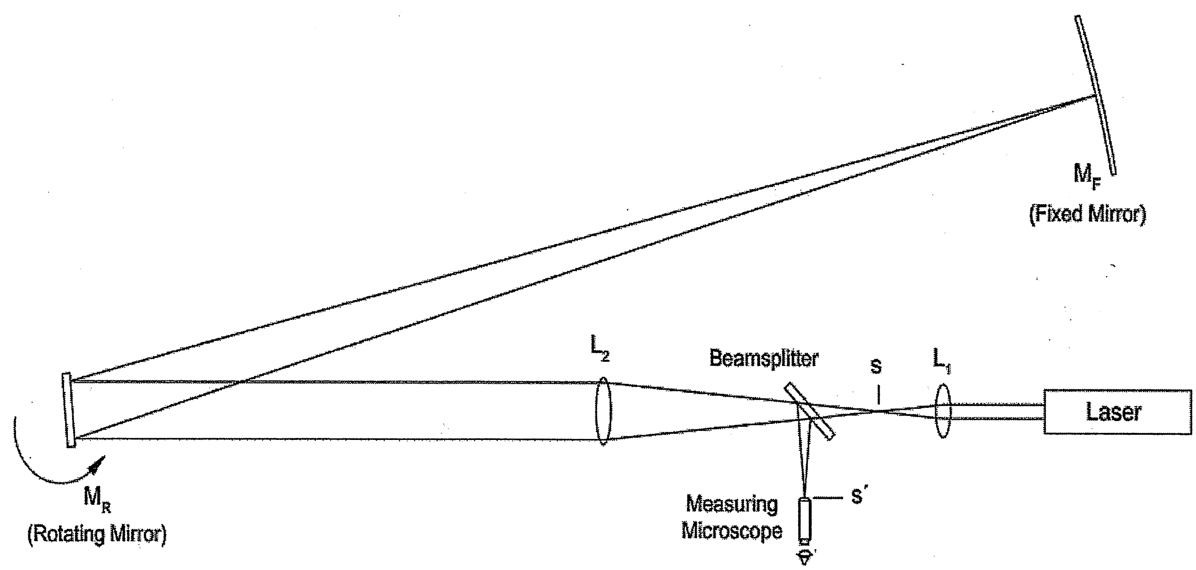

Figure 1-The Foucault Method (Reference 1)

A high speed rotating mirror assembly was used to change the speed of the rotating mirror and a measuring microscope, which is attached to the beam splitter, was used to measure the displacement of the light beam.

Theory

When using the Foucault method of determining the speed of light, the displacement of the image point of the laser beam is used, rather than using a distance and time to calculate a velocity. There are several variables that affect the amount off displacement observed. Just as Fizeau and Foucault used a rotating cogwheel and mirror, the rate at which the rotating mirror is important. The distance light travels from the revolving mirror to the fixed mirror and back is also important to the eventual calculation, along with the magnifications of the two lenses and the distances between all of them.

The beam of light takes a trip through several lenses and mirrors to eventually reach the microscope where its displacement can be measured. As described above, the beam is focused to an image point, reflected from the rotating mirror to the fixed mirror and back. Finally, it is reflected from the rotating mirror to the beam splitter and into the microscope.

The rotating mirror reflects light at a specific angle to the fixed mirror, and this angle is related to the rotational angle of the rotating mirror. The light hits the fixed mirror at a specific point, S. The angle of incidence is equal to the angle of reflection, therefore when the rotating mirror (M_R) is at an angle of θ and the laser beam strikes the M_R at an angle of θ, the total angle between the incident and reflected light path is 2θ.

Light also leaves the laser at a slightly later time when M_R has rotated slightly past the angle θ, so now the mirror is at a new angle, θ_1. The changing angle causes the light to his the fixed mirror at a new location, S_1. With this change and slight rotation, we find that

$$\theta_1 = \theta + \Delta\theta$$

and because the incident and reflected light rays are equal, we can then say

$$2\theta_1 = 2(\theta + \Delta\theta)$$

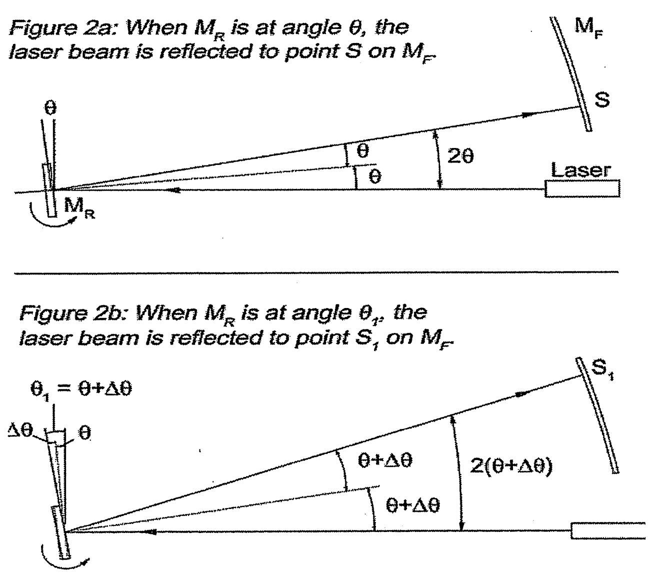

Figure 2 The Reflection Point on Fixed Mirror (Reference 1)

As seen in Figure 2 above, this change in angle causes a displacement in the image point on M_F. The distance between M_R and M_F is measurable and known, and will be called D. With this knowledge, the displacement of the light on M_F can be calculated as follows:

$$S_1 - S = D(2\theta_1 - 2\theta)$$

$$S_1 - S = D[2(\theta + \Delta\theta) - 2\theta]$$

Equation 1: $\mathbf{S_1 - S = 2D\Delta\theta}$

Next, it is important to think about where the image point will be on the beam splitter in two situations. The first situation is when the light beam strikes M_R when the mirror is at angle θ, and is reflected to point S on M_F. If the rotating mirror is stationary, the beam of light will follow the same path back, reflect off the stationary M_R and will be focused at point s on the beam splitter. However, in a second situation, M_R is now rotating, and in the time it took for the light beam to reflect off M_R at angle θ, strike M_F, and return to M_R, the mirror has continued rotating, and is at a new angle, θ_1. This appears to be similar to the first step of the derivation, however in order to fully understand it, thin lens optics must be applied.

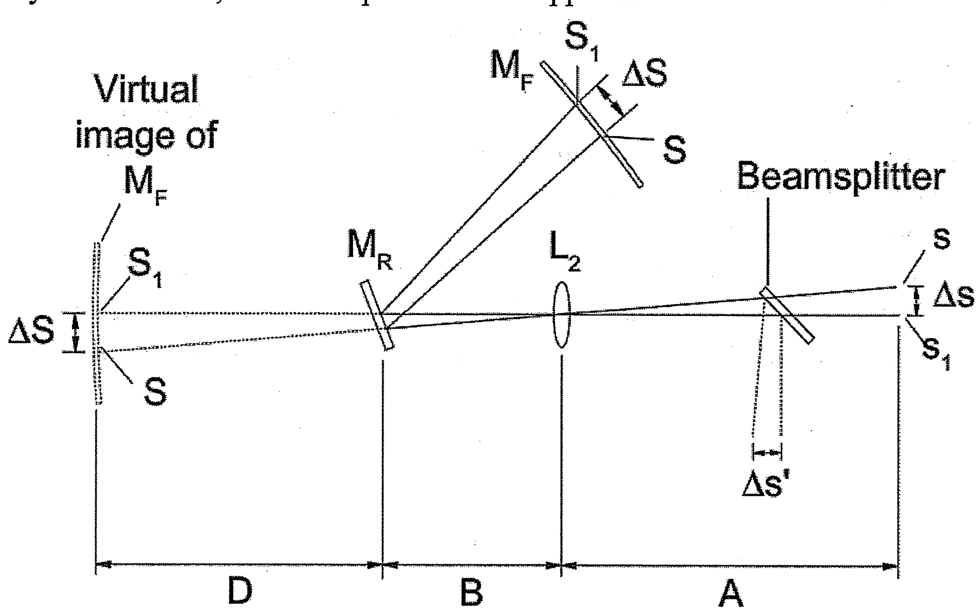

Figure 3 Thin Lens Theory Description (Reference 1)

The displacement that will ultimately be used to observe the speed of light is the Δs\`, which is the displacement of light on the beam splitter, as shown in Figure 3. When using critical geometry of virtual optics, it can be said that ΔS, which is the displacement of the light beam at the two angles, θ and θ_1, is the height of the virtual image for M_F. The light reflecting from M_F to M_R will be focused through L_2 and onto the beam splitter, forming an image of height Δs behind the beam splitter.

The displacement of the light on the beam splitter Δs\` is equal to the image height behind the beam splitter (Δs) and can be written as follows:

$$\Delta s` = \Delta s = \frac{i}{o}\Delta S$$

The distance from L_2 to the object s is i, while the distance from L_2 to the virtual image S is o. These can be restated based on the distances labeled in Figure 3 as follows:

$$\textbf{Equation 2: } \Delta s` = \frac{A}{D+B}\,\Delta S$$

The first two equations can then be combined to form the following equation that relates to the initial and secondary positions of the rotating mirror:

$$\textbf{Equation 3: } \Delta s` = \frac{2DA\Delta\theta}{D+B}$$

The angle Δθ is dependent on the rotational velocity of M_R and the time it takes the light beam to go back and forth between M_R and M_F, which covers a distance of 2D. This gives us the following equation:

$$\textbf{Equation 4: } \Delta\theta = \frac{2D\omega}{c}$$

Equation 4 can then be substituted into Equation 3 to give Equation 5:

$$\textbf{Equation 5: } \Delta s` = \frac{4AD^2\omega}{c(D+B)}$$

Finally, Equation 5 can be rearranged to determine the speed of light:

$$\textbf{Equation 6: } c = \frac{4AD^2\omega}{\Delta s`\,(D+B)}$$

Data and Analysis

In collecting data to measure the speed of light, the readings of two variables were recorded. These two variables, rotational speed of the rotating mirror and displacement of the light beam, can be seen in Tables 1 and 2. Two rotational velocities were measured for each trial, one with the mirror rotating clockwise and the other with the mirror rotating counterclockwise. Table 1 shows the velocities recorded during the ten trials.

Table 1

Trials	Rotational Speed clockwise (rev/sec)	Rotational Speed counter clockwise (rev/sec)
1	1003	1006
2	1018	1091
3	1016	1034
4	1018	1017
5	1045	1045
6	1010	1007
7	1024	1022
8	1019	1026
9	1006	1007
10	1031	1030

Table 1 shows the velocities of the rotating mirror.

Along with the rotational speed, the displacement of the light beam was also recorded. This change in the beam of light comes about from the change in the angle of reflection of the rotating mirror. Recording this displacement gives us the Δs` necessary to determine the speed of light. The displacements for each trial (one in the clockwise direction, one in the counterclockwise direction) can be seen in Table 2 below.

Table 2

Trials	Displacement clockwise (m)	Displacement counter clockwise(m)
1	1.1114×10^{-2}	1.0175×10^{-2}
2	1.1116×10^{-2}	1.0171×10^{-2}
3	1.1122×10^{-2}	1.0179×10^{-2}
4	1.1125×10^{-2}	1.0178×10^{-2}
5	1.1127×10^{-2}	1.0168×10^{-2}
6	1.1120×10^{-2}	1.0173×10^{-2}
7	1.1129×10^{-2}	1.0170×10^{-2}
8	1.1124×10^{-2}	1.0176×10^{-2}
9	1.1119×10^{-2}	1.0171×10^{-2}
10	1.1128×10^{-2}	1.0180×10^{-2}

Table 2 shows the displacement of the light beam.

Using Equation 6 from above and the data collected during the experiment, the speed of light can be determined. However, in order to make an accurate calculation, Equation 6 must be manipulated slightly to use the data and units recorded. The new equation, Equation 7, can be seen below:

$$\text{Equation 7: } c = \frac{8\pi A D^2(\omega_{cw} - \omega_{ccw})}{(s`_{cw} - s`_{ccw})\,(D+B)}$$

The differences included in Equation 7 allow for the rotational velocity to be expressed in revolutions per second, and accommodate for two readings for each trial, in the clockwise and counterclockwise direction. The counterclockwise rotational velocity is a negative number in order to account for the negative direction of rotation, so when calculating the speed of light, the velocities from both parts of a trial are added together.

The results from the measurements recorded in Tables 1 and 2 were used in Equation 7, along with the constant measured values of A, B, and D. A is the distance L_2 to the edge of the optics bench and the image point (0.262 meters), B is the distance from L_2 to the rotating mirror, with the focal length of L_2 subtracted from it (0.492), and D is the distance from M_F to M_R. The speed of light for each trial was determined, as shown below in Table 3.

Table 3

Trial	Speed of Light (m/sec)
1	1.7919×10^{8}
2	1.8692×10^{8}
3	1.8207×10^{8}
4	1.7998×10^{8}
5	1.8253×10^{8}
6	1.7838×10^{8}
7	1.7869×10^{8}
8	1.8067×10^{8}
9	1.7784×10^{8}
10	1.8208×10^{8}
Average	$1.8084 \times 10^{8} \pm 2.71 \times 10^{6}$

Table 3 shows the analysis and Speed of Light calculations.

Results

As seen in Table 3, ten trials were executed and a speed of light was determined for each of the trials using Equation 7. The average of the ten trials resulted in a speed of light of 1.8084×10^8 m/sec ± 2.71×10^6 m/sec. The standard deviation is not as large as the result, which shows that the data collected was fairly consistent over the ten trials. This result was 39% off the presently accepted value of 2.99792458×10^8 m/sec. Although this error isn't the greatest result, given the number of values that were necessary to measure very precisely and consistently, the result isn't terrible. The distance from the rotating mirror to the fixed mirror was the most difficult to measure, as there was just no easy way to do it. The calculations of the speed of light could be systematically too low due to an under measurement of this distance.

Conclusion

Overall, despite not being able to calculate a speed of light quite as effectively as the greats in the world of physics, this experiment gave some insight as to why it took so many different scientists and so many varying experiments to finally produce an accurate reading of the speed of light. Now that the speed of light is a known constant, scientists have been able to use it to make strides toward determining the age of the universe, along with being able to measure the distances to stars, planets, and other galaxies Nothing in the known world is able to exceed the speed at which light travels, which allows scientists to study the world, planets, stars, and far away galaxies with great accuracy (Reference 5).

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Millikan Oil Drop

Rachel Brandt and Dylan Helberg

Abstract: Under the guidelines of the Pasco Scientific model we sought to measure the charge of an electron via the Millikan Oil Drop. We sent oil drops through charged capacitors through switching the field of the capacitor plates the drops rise rapidly and cling to the plates, fall rapidly, or in the ground state drift downward. We measured the charge of an electron to be: 1.466 $x10^{-19}$ C compared to 1.6 $x10^{-19}$ C this is an 8.3% error.

History:

In the late nineteenth century the race was on to find the charge of an electron accurately. In 1897 John Townsend used electrolysis to yield a cloud of water droplets, measuring the mass and charge of the entire cloud he hope to find the charge on each particle. However Townsend had issues with his cloud evaporating and the accuracy of his measurements was off. Later in 1909, Robert Millikan came up with a way to eliminate the evaporation problem by using oil droplets, he also figured out a way to keep the cloud stationary with an electric field to hold the a portion of the cloud in one place (Tipler, 105). Sending the oil drops through an electric field makes the most of the drops stick to the capacitor plates. Some drops with similar charges will stick to the plate resisting gravity, and others with different charge will fall in line with gravity. Ionizing the field will change the mass of the droplets so that some will fall faster than others (106). When the field on the capacitor plates is switched (positive, negative, and ground) the drops will either fall rapidly, rise quickly, or drift downward. This manipulation allowed Millikan to observe and measure individual properties of oil droplets. He found that the charge of an electron varies in multiples, the smallest of which he determined was the value of e (Tipler 107). Millikan's value of the electron 4.77×10^{-10} e.s.u was accepted until 1928 when more precise measurements with x-ray diffractions of crystals produced the number 4.88×10^{-10} e.s.u. or 1.6×10^{-19}C. Millikan's shortcomings were later traced to a too low number for the viscosity of air. (Pasco Scientific).

Theory: Symbols for equations:

- ρ= density of oil in kg/m^3
- g= acceleration of gravity in m/s^2
- n= viscosity of air in pose (Ns/m^2)
- p= barometric pressure in pascals
- a= radius of the drop in m
- V_f= velocity of fall m/s
- V_r= velocity of rise m/s
- V= potential difference across the plates in volts

The radius of the oil drop can be calculated using equation 1: $a = \sqrt{(\frac{b}{2p})^2 + \frac{9nvf}{2g(\rho)}} - \frac{b}{2p}$ Then the mass of the oil drop can be found using the radius in equation 1. Equation 2 is as follows:

$m=4/3\pi a^3\rho$ so $m=4/3\pi\, [\sqrt{(\frac{b}{2p})^2 + \frac{9nvf}{2g(\rho)}} - \frac{b}{2p}]^3\rho$ Then once the mass and radius are found the charge carried by the oil drop is $q= mg(v_f+v_r)/Ev_f$ where E=volts/300dcm so equation 3 is

$q=4/3\pi\rho g\, [\sqrt{(\frac{b}{2p})^2 + \frac{9nvf}{2g(\rho)}} - \frac{b}{2p}]^3\frac{(vf+vr)}{Evf}$ (Equations come from Pasco Scientific).

Method:

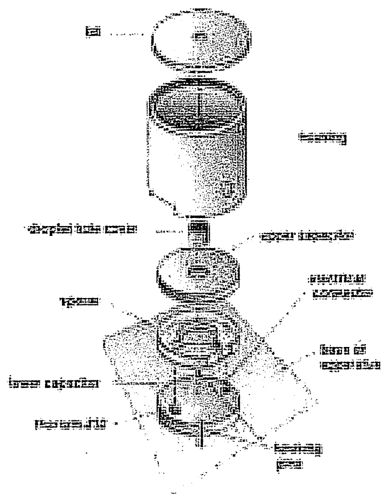


Figure 1 The capacitor chamber

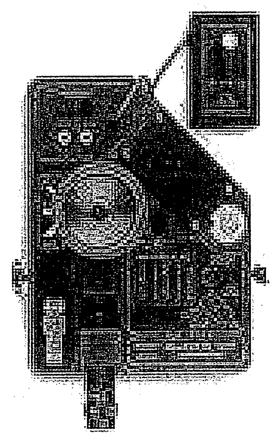


Figure 2 Millikan Oil drop Apparatus

The apparatus is set up so that the oil drop is sent into a cylinder surrounding the capacitors. The entrance to the capacitors is small and the spacing between the two capacitors is approximately 7.6mm deep. The capacitors are connected to a light source and a dc power supply. The viewing scope can be adjusted to center the viewing screen so that easy measurement of the droplets movement can be obtained. A stop watch suffices the instrument to measure the time the drop takes to travel .05mm up or down the chamber. Figure 1 shows the intricate nature of the capacitor chamber and the many parts to assembly. From the lid at the top, to the droplet hole cover, upper capacitor, spacer, lower capacitor, and base. To charge the particles the switch can be negative, grounded, or positive; we found that the grounded plates allowed the drop to fall where the charged plates usually sent them upward (Pasco Scientific). Figure 2 shows the base of Pasco Scientific's Millikan oil drop apparatus, the study base has a light source that is sent into the circular chamber, the microscope at the left bottom magnifies the oil drop's journey. The switch in the upper right corner changes the charge of the capacitors. (Pasco Scientific).

Data:

Air Pressure: 206842 Pascal

Voltage: 500.4 V

Viscosity of air: 1.852×10^{-5} Ns/m^{-2}

+Down(s)	-Up(s)
1.88	2.94
2.03	3.08
2.10	2.79
1.94	2.09
1.78	3.22

Radius of oil droplet: 1.56×10^{-5} m

Vf=2.56×10^{-5} m/s Vr = 1.77×10^{-5} m/s

Charge of Electron: 4.68×10^{-10} e.s.u. 1.56×10^{-19} C

Percent Error: 2.56%

+Down(s)	-Up(s)
1.19	1.37
2.06	2.90
2.29	2.81
2.40	2.94
2.28	2.78

Radius of oil droplet: 1.52×10^{-4} m

Vf=2.44×10^{-5} m/s Vr= 1.95×10^{-5} m/s

Charge of Electron: 4.62×10^{-10} e.s.u. 1.54×10^{-19} C

Percent Error: 4.48%

+Down(s)	-Up(s)
2.08	2.68
2.28	2.18
2.32	1.89
2.13	1.50
1.37	1.50

Radius of oil droplet: 1.55×10^{-4} m

Vf= 2.45×10^{-5} m/s Vr= 2.56×10^{-5} m/s

Charge of Electron: 5.29×10^{-10} e.s.u. 1.76×10^{-19} C

Percent Error: 10.1%

Particles four and five: viscosity of air 1.856 x10^{-5} Ns/m^{-2}

+Down(s)	-Up(s)
2.88	3.18
3.03	2.59
2.81	3.00
1.78	2.38
2.72	2.28

Radius of oil droplet: 1.35x10^{-4}

Vf=1.89 x10^{-5} m/s Vr= 1.86 x10^{-5} m/s

Charge of Electron: 3.53x10^{-10} e.s.u. 1.18 x10^{-19} C

Percent Error: 26.5%

+Down(s)	-Up(s)
2.79	2.28
2.31	2.50
2.81	3.00
1.78	2.38
2.72	2.28

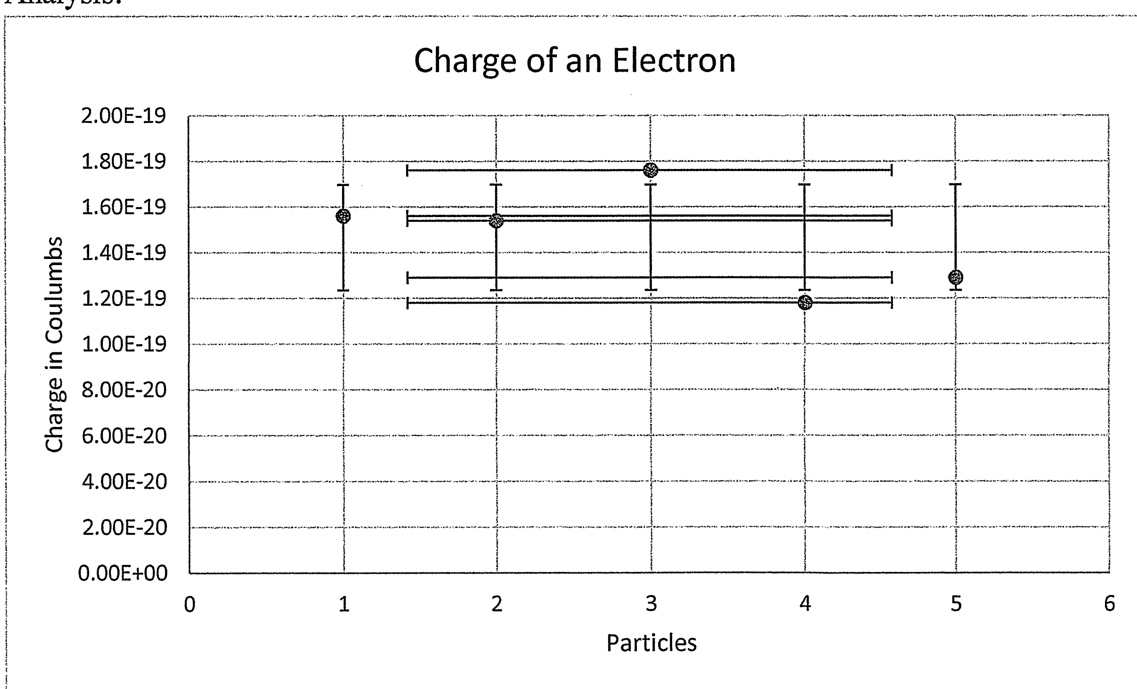
Radius of oil droplet: 1.35x10^{-4}

Vf=1.90 x10^{-5} m/s Vr=2.22 x10^{-5} m/s

Charge of Electron: 3.89x10^{-10} e.s.u. 1.29 x10^{-19} C

Percent Error: 19%

Analysis:



Average Value for the charge of an electron: 1.466 x10^{-19} C compared to 1.6 x10^{-19} C this is an 8.3% error.

Conclusion:

After connecting the Millikan oil drop apparatus to a power supply with 500.4 volts we measured the resistance to determine the temperature and viscosity of air. For particles 1-3 the viscosity was 1.852×10^{-5} Ns/m^{-2} for particles 4&5 the viscosity was 1.856×10^{-5} Ns/m^{-2}. Then we sprayed oil into the capacitor chamber, after manipulating the particles via switching the charge of the plates to move the particle up and down we recorded the rise and fall velocities of five oil drops. Then we determined the radius, mass, and charge of an electron. We determined the charge of an electron to be 1.466×10^{-19} C compared to 1.6×10^{-19} C this is an 8.3% error. We could improve measurements by selecting particles that when neutral drift downward at a slower pace, as these have less excess electrons, or by cleaning out the capacitor chamber after each time spraying oil as the apparatus works better when clean. Our last measurements were the least precise as the chamber was clogged with oil.

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Joseph Koenig,
Andrew Yerrell
Advance Physics Lab
Lab write up
12/2/2014

Gravitational Torsion

Abstract

History is dotted with many great scientific discoveries. From how the body fights off viruses to the element that makes up everything around us. None seem to be as important as the one that keeps us on the ground. The gravitational constant is not just a number for us to calculate equations in class. This constant allows for Astronauts to go into space and us to walk around. The original experiment was the first to measure an accurate number for the gravitational constant between two masses. Using an updated experiment we took a more modern physics approach. Combine the pendulum oscillation with a laser and we are able to get a new way to calculate the gravitational constant.

Introduction

The first gravitational torsion experiment was conducted in 1787 by a British scientist Henry Cavendish. The apparatus was originally designed by John Michell but he died before he was able to conduct any experiment. The apparatus was then handed down to Cavendish who was then the first conduct an experiment. The original apparatus was designed very simple. It was a long rod which had a wire that attached to it so that it could hang free in space. There were weights add on to the rod. This would cause the rod to twist back and forth. Once it was settled two smaller weights were placed opposite the main weights. This would cause more twisting but after a while it would become more harmonic in movement. Similar to a pendulum it would go back and forth. The torque produced could be easily measured. Combined with

Collected below are 59 points each point has a corresponding position along a number line. The number line was 7.95 meters away from the apparatus. The distance from the apparatus to the measuring point does not have any affect on the pendulum or the data point collected.

Point number	Distance from Origin in cm		
1	1.351	16	2.35
2	.15	17	4.10
3	3.90	18	4.45
4	11.10	19	4.95
5	9.30	20	3.85
6	9.70	21	3.50
7	20.45	22	3.60
8	18.05	23	7.45
9	3.55	24	3.70
10	4.45	25	8.50
11	2.90	26	4.65
12	3.20	27	8.45
13	8.95	28	5.65
14	2.70	29	8.30
15	3.15	30	6.90

31	5.25	47	2.05
32	2.30	48	2.50
33	8.20	49	3.05
34	9.50	50	2.25

35	4.35	51	2.90
36	6.00	52	2.80
37	6.25	53	2.55
38	.85	54	3.25
39	8.00	55	2.95
40	4.15	56	2.45
41	6.45	57	2.15
42	2.75	58	2.25
43	3.30	59	2.50
44	4.15	60	
45	2.90	Base Point	2.40 cm
46	3.10		

Starting for the equation for the gravitational attraction the final equation for the torsion can be derived

F = Gm1m2/b

we can then say that the torsion can be stated as follows

$$t_{grav} = 2Fd$$

$$t_{band} = -\kappa\theta$$

κθ = 2dGm1m2/b2

by rearranging the equation above we can get an equation for gravity we also need to account for some of the other things like inertia of the rings. This leads to a final equation that can be stated as such.

$$G = \pi^2 \Delta S b^2 \frac{d^2 + \frac{2}{5r^2}}{T^2 \quad m_1 L d}$$

gravity constant calculated	9.75

This experiment generates a number that is close to what we know as the gravitational constant. The fact that we can measure the force of gravity from a couple of massed on a stand. The other fact that it is measured using a laser that is reflecting a beam of light on a wall.

Bibliography

PASCO lab manual

Finding the Gravitational Constant With A Torsion Balance

Andrew Yerrell and Joe Koenig

(November 23, 2014)

The universal gravitational constant has been experimentally known for over 200 years. Using a modern torsion balance, we calculated our own experimental value for G. With Pasco's torsion balance set up a distance from a writing surface and using a laser to shine onto the balance while marking points on the surface over a time interval, we conducted our gravitational constant experiment. Our value was slightly off from the theoretical value of G. This experiment can be easy to understand and done by many college students looking to understand gravitational force.

I. Introduction

Gravitational attraction has been studied for many of years, even back to Newton's age when he first used the term "gravity". The law of universal gravitation that he proposed stated that the gravitational attraction between any two objects is proportional to the product of the two masses over the square of the distance between there center of masses. G is the universal gravitational constant for all matter (Source 1). In the experiment, the goal was to experimentally calculate this value of G using a torsion balance. The experiment uses basic physical properties of torque and oscillations to calculate this value. G was not experimentally calculated until 1798 when Lord Henry Cavendish built his version of the torsion balance. Figure 1 displays a reconstruction of his apparatus.

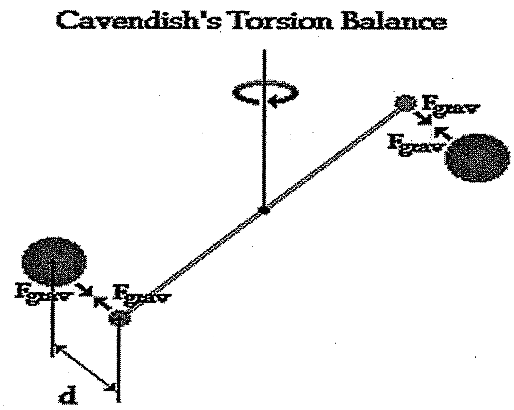


Figure 1

The apparatus consisted of a 2 foot rod with two small lead spheres attached to the ends. The rod was then suspended in the middle by a thin wire. Two other larger spheres were place on each side of the small lead spheres. The attraction of the gravitational force caused the rod to rotate while the torsional force counteracted the gravitational force to meet equilibrium. His apparatus was constructed in a way to determine the correlation between the angle of the rotations and the amount of torsional force on the wire. When the rod and spheres came to rest, Cavendish was able to measure the force due to gravitational attraction. He measured G to be 6.75×10^{-11} N m^2/kg^2 which was very close to the accepted value used today (Source 1). Doing this experiment one can find how small the value of G actually is and how it contributes to objects attraction force. Because of the small value only very massive objects actually feel a noticeable attractive force (such as planets).

II. Experimental Setup

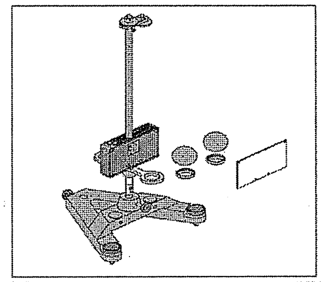


Figure 2

In the experiment conducted, Pasco scientific has produced a modern version of Cavendish' torsion balance. As you can see from figure 2 above it is very similar. The major difference in this setup is that a small mirror is attached to the wire. A fixed laser is then setup to shine off of the mirror and reflect back to a surface some distance L away. Special care is taken in this setup in order to not break the wire. In the setup, one should make sure to set the torsion stand on a sturdy table in a room that has minimal disturbance (Pasco).

III. Theory

The law of universal gravitation is displayed in equation 1 below,

$$F = Gm_1m_2/b^2$$

Which is the driving equation in the experiment. The variable b in this equation is the distance between the centers of the two masses. In the experiment and after, one will wait until the system is in equilibrium before beginning. When changing the orientation of the large masses on the apparatus, the gravitational attraction between the masses will create a net torque on the system represented by equation 2,

$$\tau_{grav} = 2Fd$$

Where d is the length of the lever arm. Because the system is in equilibrium before changing the orientation, an equal and opposite torque is created to bring the system back to equilibrium. The torque is equivalent to the torsion constant times the angle of which the system twists. Equation 3 represents below represents this torque,

$$\tau_{band} = -\kappa\theta$$

k is the torsion constant and theta is the angle of twisting. To further understand the "angle of twisting" see figure 3. Figure 3 shows how the angle is measured by using the laser to reflect the light at a wall that will be at equilibrium at two different spots S_1 and S_2. The angle is calculated using trigonometry where theta ultimately is equivalent to the ΔS divided by 4L.

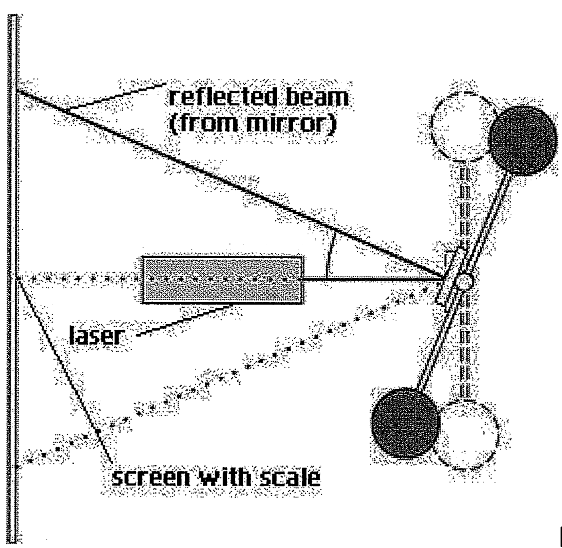


Figure 3

To solve for kappa in the experiment we must calculate the period of oscillations after the changing of orientation of the spheres. Kappa is related to the period in equation 4 below,

$$T^2 = 4\pi^2 I/\kappa$$

The moment of inertia I is equivalent to $2m_2(d^2 + {}^2/_5\, r^2)$ because the small masses that make up the pendulum create this inertia where d is the distance between the center of the masses to the torsion axis and r is the radius of the spherical masses. The experiment is used to determine the period, and ΔS in the equations. By putting the inertia in for I and solving for k, equation 5 is produced,

$$\kappa = 8\pi^2 m_2 \frac{d^2 + {}^2/_5\, r^2}{T^2}$$

Finally, setting equation 2 equal to the negative of equation 3 and using equation 5 for k, one can solve for the force F and use that force in equation 1 . Solving for G gives the final equation,

$$G = \pi^2 \Delta S b^2 \frac{d^2 + {}^2/_5\, r^2}{T^2 m_1 L d}$$

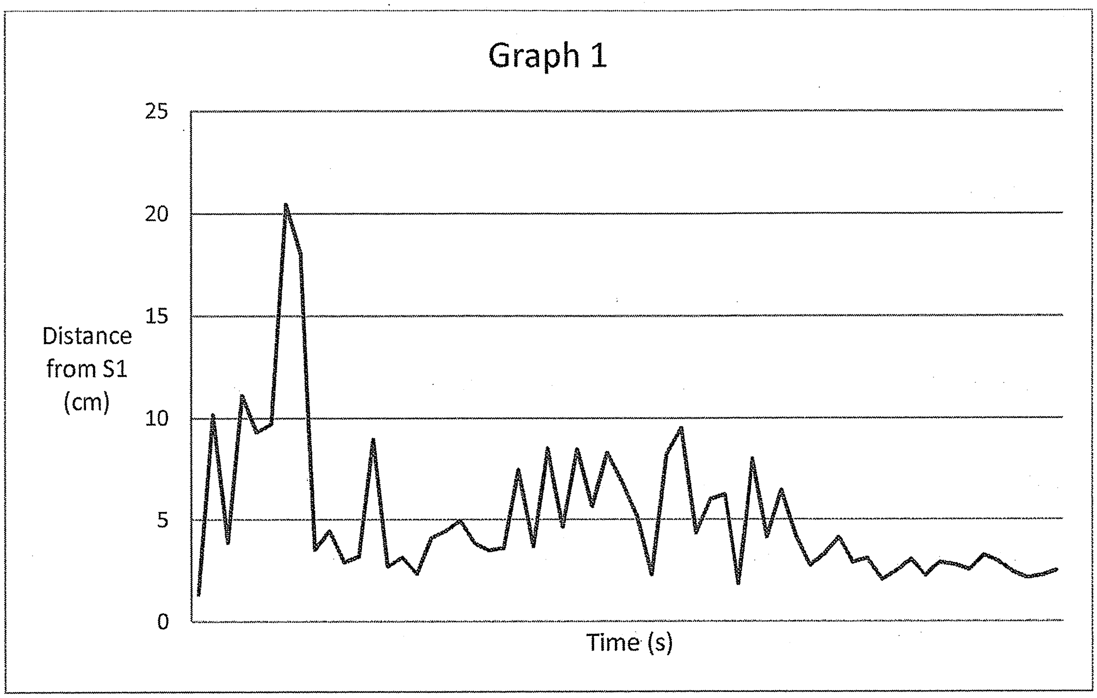
G is what we now know as the universal gravitational constant (Pasco).

IV. Method

The gravitational torsion balance was produced by Pasco scientific to measure the universal gravitational constant. The initial setup of the experiment did not take long but took a lot of precision. We placed the stand on a sturdy table in a room with little disturbance. After placing the torsion on the stand, we attached a ground wire to the system to take away the charge so that a force is not produced from charged particles. After, we leveled the stand in relation to the pendulum bob that can be seen through the sight in a mirror reflection. It is important that the pendulum bob is centered. The large masses were then placed on the case plates and rotate the case plates to a position closest to the small masses; the side chosen does not matter. We let the apparatus sit over night or for an extended period of time so that the pendulum could reach equilibrium. To begin the actual experiment, we had to shine a laser on the pendulum mirror and have it reflect to a large piece of paper or surface that we could write on. We measured the distance from the mirror to the surface which is L in your final equation. Then, we marked on the surface where the beginning equilibrium is as S_1. We shifted the case plates to the opposite side very carefully and waited until the oscillations on the surface were not sporadic and rather smooth. We then started a stop watch and marked where the light was shining in its oscillation. This we repeated every 15 seconds until we had 60 points of data. We made sure to label each mark in order because the marks needed to be measured later in respect to S_1. We let the system oscillate even longer until it reached a point of equilibrium. We recorded this point as S_2. Using a ruler or meter stick, we measured the distances of each point from S_1 and recorded the data. This experiment takes extreme precision and is hard to do. It is recommended to use a partner in the process.

V. Data and Analysis

In our experiment, the apparatus was placed 7.95 meters away from the projecting surface. From the data points taken every 15 seconds, we measured the distances displayed in graph 1.



Graph one is a line graph that connects the points to show a trend of oscillations. By the end of the graph the oscillations become smaller and smaller. Eventually it reaches an equilibrium around 2.4 centimeters away from S_1. To estimate T (the period), we took an average of 6 half periods throughout graph 1 because the period cannot be clearly seen from the graph. We found T≈88.3 seconds.

VI. Results

By using our results and the known constants from the Pasco manual we determined our experimental value of G to be $2.79\times10^{-10} N\, {m^2}/{kg^2}$. The accepted value by scientists is 6.673x10$^{-11}N\,{m^2}/{kg^2}$. Our value was slightly off the actual value where we had a percent error of 318%. The experiment we conducted was in a room in the basement of a universities science building. The apparatus used was very sensitive to light and would oscillate on its own due to sound and movement. The building is constantly occupied and the actions of other people affected the experiment. This and other factors contributed to the error in the experimental value.

VII. Conclusion

Our experiment was to calculate the universal gravitational constant using a torsion balance. We calculated the constant to be 2.79x10$^{-10}N\,{m^2}/{kg^2}$ which was miss calculated by 318%. To further this experiment for better results one might use an isolated room and building with sturdy foundation. I would also recommend an easier way of marking data points and measuring distances. A programmed sensor board that could calculate the lasers position over time would be ideal for this experiment instead of marking by hand and measuring. Knowing how small this constant is helped us understand how large masses and short distances are the main contributors to objects feeling a noticeable gravitational force.

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