The Speed of Light: Historical Perspective and Experimental Findings
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The purpose of this paper is to analyze several historic and modern methods of determining the speed of light in a vacuum. The speed of light is a very important constant in the concepts of optics and modern (post-1900) physics, particularly special relativity and quantum mechanics. We shall also describe our laboratory experimentation results from a classical measurement technique and a modern technique: Foucault’s historical rotating mirror experiment as well as a laser-based experiment from which the currently accepted value is derived.

Historical Perspective

The speed of light and light emission have fascinated scientists every since they first glimpsed at the sun. Until the last 25 years, the exact speed of light had not been known. Roughly 2500 years ago, most philosophers and scientists were under the general belief that the speed of light was infinite; although it should be noted that most of these ancient visionaries were still trying to decide whether vision, and thus light, was created by the eye itself or the visible object. The best noted exception to this general belief was Empedocles of Acragas. Aristotle said “(Empedocles) was wrong in speaking of light as ‘traveling’ or being at a given moment between the earth and its’ envelope, its movement being unobservable to us.” An unordinary proof that the speed of light must be finite was given by Heron of Alexandria. Heron stated that if you close your eyes, turn you head toward the stars, and then suddenly open your eyes, you immediately see the stars. Heron reasoned that since no time elapsed between opening and seeing that light must travel instantaneously. Heron’s reasoning seems exceptionally found considering his belief that vision was caused by an emission from the eye.1

Around 1000 AD two Islamic Scientists, Avicenna and Alhazen separately stated that light must have a finite value. Avicenna stated that since light is due to emission of some sort of particle (now known as the wave-particle duality of light) then
the speed of light must be finite. Alhazen affirmed that light is movement; therefore it is at one instant in one place and at another instant in another place. Since it is impossible for light to be in both places at the same time, the transmission of light cannot be instantaneous. Sir Francis Bacon stated in 1620 “Even in sight, whereof the action is most rapid, it appears that there are required certain moments of time for its accomplishment… [for there are] things which by reason of the velocity of motion cannot be seen – as when a ball is discharged from a musket…” There was still uncertainty seen by Bacon’s contemporary, Johann Kepler. Kepler was famous for his work on planetary motion. Kepler reasoned that since light could be propagated into illimitable space, it required no time. Since light did not need time, it was immaterial and could offer no resistance to a moving force. Thus according to Aristotelian mechanics (a now archaic form of mechanics that would be superseded by Newtonian mechanics at least 40 years after Kepler’s death) light must have an infinite velocity.2

The First Experiments to Determine the Speed of Light

A contemporary of Kepler and Bacon, was Galileo Galilei. Galileo was the first person to actually attempt to measure the speed of light. Galileo devised that two people should go stand with covered lanterns a known distance apart. When one uncovered their lantern, the other would quickly uncover his lantern and the time difference would be measured. After testing this experiment at a distance less than one mile, Galileo concluded: “I have not been able to ascertain with certainty whether the appearance of the opposite light was instantaneous or not; but if not instantaneous it is extraordinarily rapid – I should call it momentary.” 2 It could be said that Galileo at least established a lower limit for the speed of light. It is known today that about a thirtieth of a second is the minimum time interval distinguishable by the unaided, human eye. Then Galileo’s experiment put a lower limit of about 9.65 x 10^4 meters per second (m/s) on the speed of light; which is about 3000 times less than the currently accepted value. Renee Descartes sought to get an actual number by greatly increasing the distance. Descartes proposed that if light was finite with time than eclipses of the moon would be visible on earth later than when the sun, moon and earth were calculated to be in a straight line. When no delay was detected, Descartes proceeded to declare that light must be instantaneous. 3
Given the failure of Galileo and Descartes, Ole Roemer sought to determine the velocity of light by observing even further distances. Roemer studied the eclipses of Jupiter’s moon, Io. Roemer timed the moment that Io became hidden by Jupiter and then the moment that it reappeared. He would then compare this time interval as Earth moved closer and further away from Jupiter. Roemer realized that as Earth moved away from Jupiter, the time interval for time spent hidden increased. As earth rotated back closer to Jupiter, the hidden time interval would slowly decrease. Although Roemer himself never actually gave a numerical value for the speed of light, he did state that light requires about a second (s) of time to traverse a distance equal to the diameter of the earth. From this statement it can be deduced that light would require 22 minutes to traverse the earth’s orbit. These numbers were combined by Christian Huygens to give the value of $2.20 \times 10^8$ m/s which gives a percent error of about 26% from the currently accepted value. Although the value is inaccurate, it was the first reproducible result for the speed of light and gave proof that the speed of light was finite.

For the next 150 years people would continue to adapt Roemer’s experiment and come up with a multitude of values for the speed of light. Even Isaac Newton attempted to determine the speed of light and predicted it to be about $2.41 \times 10^8$ m/s. Newton derived his speed using Cassini’s value for the retardation of light from the sun and his own guess that the distance from the earth to the sun was approximately $1.12 \times 10^{11}$ meters (m). If Newton had used Cassini’s own value for the distance from the earth to the sun, $1.46 \times 10^{11}$ m, he would have arrived at a speed of light of approximately $3.05 \times 10^8$ m/s, only a 2 percent error from the now accepted value.

Up until the 1840s, no one had been able to determine an accurate measurement for the speed of light using only terrestrial measurements. In 1849, Armand Fizeau sought to remedy this problem. Fizeau set up a rotating cog wheel with 720 teeth spinning at 12.6 revolutions per second (rev/s). Fizeau sent a lamp beam through the teeth and then 8 kilometers ($10^3$ m) away to a mirror. Upon returning, the beam was brought though the gaps of the teeth. As the light passed through the gaps on
their return, the light was blocked by the teeth as they moved into the position of the gaps. The time taken for the teeth to move this distance was equal to the time taken for the light to travel to the mirror and back, 16 km. Using simple math he obtained a value of $3.15 \times 10^8$ m/s; roughly 5% too high. Fizeau’s former friend/partner Leon Foucault would use the same concept in 1862 except with a spinning mirror and determine the speed of light to be $2.98 \times 10^8$ m/s, within 1% of the correct value.

An important revelation came about near the end of the nineteenth century. At the time, the theory of light acting as a wave was well accepted by the scientific community, thanks to the earlier work of Thomas Young and Augustin Fresnel. However, there was a troubling problem in the conventional logic: If light is a wave, then there must exist some form of medium upon which it travels, as all other known waves did have a medium of transmission. In 1873, James Clerk Maxwell used his electromagnetic theory of light to determine the speed of light in a vacuum mathematically (See appendix 1 for a derivation):

$$c = \sqrt{\frac{1}{\mu_0 \varepsilon_0}} = 2.99792458 \times 10^8 \text{ m/s}$$

where $\mu_0$ and $\varepsilon_0$ are the permeability and permittivity of free space, respectively. He proposed that such a medium, called the “luminiferous ether” must be consistent with electromagnetic theory and that a sensitive enough instrument could discern its properties. By 1880, the concept of the ether was well accepted.

Finding this mysterious ether became the next goal of physics, and in the 1880’s, a famous experiment known as the Michelson-Morley Experiment would yield startling results. Albert Michelson developed an extremely precise instrument called the interferometer, which could detect very small phase differences between two light waves. His device used an incident beam of monochromatic light partially reflected and partially transmitted by a silvered glass surface. The light is then reflected by two mirrors at perpendicular angles (the theory being that one of the paths of light will be parallel to the Earth’s motion through the ether flow and one will be perpendicular, so there will be a phase difference between the two beams). Using classical mechanics he determined that there should be a time difference...
between the two beams of \(8 \times 10^{-17}\) s, which would result in 0.04 fringes in the interference pattern. Though his instrument should have been able to detect a pattern half the size of the expected result, he found nothing. In 1887, Michelson teamed up with Edward Morley, who would make great improvements on Michelson’s device. The path length of the device was greatly extended, increasing the expected fringe shift tenfold. Even though the device could detect a fringe shift as small as 0.005, they observed absolutely no effect. The results were consistent over several subsequent retrials, and no substantial results were ever observed. The ether did not seem to exist. Today, over a century later, there is still no realistic evidence for the ether theory. 7

Albert Michelson would then improve on Foucault’s apparatus by using better optical lenses and a longer baseline for the distance. Beginning in 1906, Michelson measured the speed of light to be \(2.99853 \times 10^8\) m/s. Over the next 25 years, Michelson would continue to revise his own experiment in search of a definitive measurement. In his final experiment, Michelson combined the most up to date electronics and optics available with a vacuum tube for his light beam. Unfortunately he did not live to see his collaborators, Pease and Pearson, publish the results of \(2.99774 \times 10^8\) m/s; this result is within .006% of today’s accepted value. 8

Using Maxwell’s theory R. Blondlot was the first to measure the product of the frequency and wavelength of an electromagnetic wave. Blondlot adapted Foucault’s apparatus to measure the speed of electricity in a conductor and found it to be very close the value found by Maxwell’s theory of \(2.99792251 \times 10^8\) m/s. 9

The 1907 experiment of E. B. Rosa and N. E. Dorsey consists of measuring the speed of light by comparing the experimentally determined capacitance of a capacitor in electromagnetic units and electrostatic units with predetermined currents from a current balance. This method produces a value of \(2.99788 \times 10^8\) m/s, which is 0.000015 % below the accepted value. 10

In 1958 K. D. Froome used klystron oscillators to measure the speed of light by analyzing both the frequency and the
wavelength of millimeter waves. There was an uncertainty resulting from the limited wavelength of possible radiation, because the longer wavelengths used in this experiment could not be measured as accurately as shorter ones. The result achieved from Froome’s work was a value of $2.997925 \times 10^8$ m/s. This result was the best of its time as laser technology was not capable of more accurate measurements.9

Modern Measurements of the Speed of Light

From 1972 to 1984, many measurements would be made using the improved technology of tungsten-nickel point contact diodes. The new diodes resulted in various speed of light measurements in laser-based experiments, such as Evanson’s 1973 experiment resulting in a speed of light value of $2.997924574 \times 10^8$ m/s. This highly accurate result is one of the many scientific benefits of stabilized lasers. Before this innovation, emission radiation from atoms was the only spectrally pure light available for testing, and the frequency of such light is difficult to control. A way of locking the frequency of the emission was necessary to accurately measure the speed of light by this method, which was found in the sub-Doppler saturated absorption spectroscopy. This technique permits the locking of frequency of the radiation into a very small window of spectral features, so that both quantities wavelength and frequency remain fixed. Since the development of sub-Doppler saturated absorption spectroscopy, several sources have been stabilized. The helium-neon with a wavelength of 3.39 µm ($10^{-6}$ m) stabilized with saturated absorption in methane. Carbon dioxide with a 10 µm wavelength stabilized to fluorescence with saturated carbon dioxide. A red helium-neon source stabilized to iodine-saturated absorption. These are the three main laser sources used to measure the speed of light, and sometimes they are combined.

In the case of Fabry-Perot interferometers, two wavelengths are compared by the observation of interference fringes of waves refracting between two mirrors. This has been used to measure the speed of light many times and normally using the standard-length 605.8 nm ($10^{-9}$ m) orange lasers using a krypton source. Unfortunately, this method results in an error of around four parts per hundred million. More accurate measurements could be made by better measurements of emission frequency. Better results were achieved with techniques using
high-speed nonlinear devices to generate harmonics. Since these measurements were based on frequency, they were ten times more accurate than wavelength-based measurements.9

These measurements showed that the uncertainty largely stemmed from the asymmetry of the krypton line, upon which the current standard meter was based. It became apparent that the accuracy of the standard meter could be greatly improved by redefinition. The direct measuring the frequency of the 633 nm iodine stabilized helium-neon laser and the 576 nm spectroscopic line of iodine, along with many other such direct measurements, was the final step to redefining the meter. In 1983, the General Conference on Weights and Measures redefined the meter as the distance traveled by light in a vacuum over a period of $1/299\,792\,458$ of a second. Consequentially, the speed of light in a vacuum is defined as a constant, not to be changed or re-measured. This definition of the meter has remained strong because a definition based on a standard such as the krypton lamp can be continuously made more accurate without the need to form a new definition for the parameters.11

Modern Reproduction of Foucault's Speed of Light Experiment

Our first experiment in the LaGrange College Physics Laboratory was closely based on the 1862 experiment by Foucault. The equipment used consisted of the PASCO Complete Speed of Light Apparatus (OS-2961A). The experiment relates the angular velocity of a rotating mirror to a spectral displacement to determine the speed of light in a vacuum.13 In our experiment; a class 2 laser (PASCO 1508-1) with a 633 nm helium-neon gas source and 0.8 miliwatt ($10^{-3}$ W) power output was used to generate our incident emission. Foucault's original experiment used a standard incandescent light source. The beam was focused through a 48 mm ($10^{-3}$ m) focal length lens placed 6.95 cm ($10^{-2}$ m) from the incident light source (which hereafter the incident source will be our reference origin for all values except the fixed mirror distance from the rotating mirror) and past a beam splitter placed at 18.22 cm. The laser beam was focused through a 252 mm focal length lens at 38.27 cm and then directed into a rotating mirror at 83 cm, from which the beam was directed at an angle of $25^\circ$ to a fixed mirror 11.407 m away. The laser beam was reflected back into the rotating mirror, which was then reflected back into the beam...
splitter. From the microscope on the beam splitter, the spectral field could be observed, and thus the image point (See Appendix 3 for diagrams).

After meticulously aligning the equipment, we were ready to begin. The emission filtering of the beam splitter produced the unique pattern of a small, sharp, bright dot (our image point) adjacent to a bright and equally sharp band, quite separate from the rest of the apparent emission in the spectral field. The rotating mirror was activated and the speed was increased to approximately 600 rotations per second (rev/s) to allow the motor to warm up. After three minutes, the speed was increased to 1,000 rev/s and then the speed to its maximum velocity, approximately 1,500 rev/s.

As the mirror rotated continuously at high velocity, a laser pulse was generated which resulted in a strange phenomenon: the incident light strikes the rotating mirror at a different angle than the reflected light thus, allowing measurable displacement with the image point to be seen. The small dot in the spectral field was displaced and measured with a micrometer. This process was repeated at least twice for each direction (clockwise and counterclockwise), and the results were tabulated. Using these results, we were able to determine a value for the speed of light of $2.992 \times 10^8$ m/s for the speed of light in air.\textsuperscript{12} The value found is 0.198% below the currently accepted value. Foucault’s original experiment produced a value of the speed of light, $c = 2.99792 \times 10^8$ m/s, approximately 1% lower than the modern value. It should be noted that in this experiment the speed of light is measured in air, the value of which mathematically should be approximately 0.03% lower. The greater precision in our results stems from several factors, almost all of them due to our equipment. We were able to use a laser light source, where Foucault had to use standard light bulb. We were also able to electronically control and measure precisely our rotation speed, whereas, Foucault did not have the use of any modern electronics.
FIGURE 1: DIAGRAM FOR THE FOUCAULT SPEED OF LIGHT SETUP

LASER EXPERIMENT TO DETERMINE THE SPEED OF LIGHT

Another more modern experiment that we performed was the determination of the speed of light using a PASCO Scientific Laser Speed of Light Apparatus (AP-8586). This approach measures the phase shift of light, compared to a reference point, as it travels different distances. This is the approach that is most commonly used today in order to determine the speed of light, or to determine the accepted value of the fundamental length in the metric system, the meter. The equipment used in this experiment consisted of: a function generator (SB-9549A), Diode Laser with power adapter (OS-8528A), component carrier (OS-9107), +127 mm lens (OS-9134), Laser Alignment Bench (OS-9172), Light receiver, 4 Stainless Steel pads, Concave Mirror Display (003-02226), a 60 MHz (10^6 Hz) oscilloscope, a tripod, a tape measure, a plumb bob and a diode laser. Most of the equipment is fairly self explanatory, but the diode laser emits an intense, narrowly-focused beam of light. In this experiment the function generator modulates the light at an intensity of approximately 3 MHz. The concave mirror helps to focus the light as it is reflected. The light receiver is designed for receiving audio and video signals transmitted via modulated light. The +127 mm lens is used to focus the light onto the element of the receiver. The experiment was conducted along the first floor hallway of the Callaway Science Building in order to increase path distance.

The laser is mounted on an L-shaped bracket with the bracket bent away from the laser. The receiver is placed at the back of the laser alignment bench, while the laser itself is mounted the very front of the bench. The bench was then
moved to the edge of the table so that an exact measurement could be taken for the distance from the mirror to the laser. Once the laser was turned on, the lens was moved in order to focus the reflected laser beam into the most precise dot onto the receiver. Different lengths are measured out on the floor ranging from approximately 1 m to 23 m. Once all of the equipment was set up, data collection could begin. The function generator is set to a square wave with a DC offset and the frequency is set to $2.683 \times 10^6$ Hertz (Hz). On the oscilloscope, channel 1 is set to 1 volt per division (V/div), direct current, channel 2 is set to 1 V/div, alternating current, and the trigger level was set to approximately 2.5 volts (V) and the base time set to 0.2 microseconds per division (µs/div). The DC offset and amplitude on the function generator is then tuned to maximize the sine wave signal on channel 2.

Using a Vernier caliper, an initial distance between the square wave of channel 1 and the sine wave of channel 2 is found to be 0.25 cm. This initial distance reading took place with the mirror at a distance from the laser of 1.080 m. This initial reading would then become the baseline for all the following measurements to be based upon. The mirror is then moved back approximately 2 m and the distance between the square wave of channel 1 and the sine wave of channel 2 is re-measured. This procedure is repeated until the distance from the mirror and the laser reaches 23 m. The change in distance of the square wave to sine wave minus the initial distance of 0.25 cm ($\Delta t$) is plotted against 2 times the laser to mirror distance minus the initial distance of 1.080 m ($\Delta d$). In order to get our $\Delta t$ measurements out of centimeters and into seconds we have to apply what we know about the set up of the equipment. Since we have the division setting on 0.2 µs/div, we measured that 1.00 cm equals 5 divisions (div) on the oscilloscope. Therefore 1 div is equal to 0.20 cm, and every cm is equal to 1 µs or 1000 nanoseconds (ns). Using Microsoft Excel, a spreadsheet and a graph were created. By connecting the data points, a line is formed and the slope of the line found. Since $\Delta t$ vs. $\Delta v$ gives the slope of the line in units of m/s. We can deduce that the slope, $2.956 \times 10^8$ m/s, is the speed of light. Our measurement is only 1.4% off from the currently accepted value of $2.99792 \times 10^8$ m/s.
TABLE OF RESULTS

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<th>Distance From Laser Source to Mirror (m)</th>
<th>Sine Wave To Square Wave Distance (cm)</th>
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In the above graph, the light grey line represents the known value for the speed of light, 0.2997 meters per nanosecond (m/ns) equivalently $2.997 \times 10^8$ m/s. The dark grey line represents the slope of our values obtained, 0.2956 m/ns or $2.956 \times 10^8$ m/s. The black t-shaped lines coming from the dark grey line represent a plus or minus 5% value. Our obtained value is only 1.36% off from the current measurement.

**Summary**

Every major scientist from Aristotle to Galileo to Newton to Michelson has pondered on the speed of light. During our history research, we discovered that there have been major attempts by a vast number of scientists in order to determine the speed of light. The value of the speed of light is crucial to Einstein’s theory of special relativity. The theory states that space and time are not a constant but; the speed of light never varies, regardless of time or space. The phenomena of time dilation and length contraction cannot be explained without an accurate value for the speed of light. We chose to do two of these experiments and compare our results with today’s accepted value. While one of our experiments was a modern interpretation of an old experiment, the other experiment used modern standards and both were accurate in determining the speed of light to within 2% of the currently accepted value of $2.99792 \times 10^8$ m/s.
WORKS CITED

6. See appendix 1 for derivation
12. See appendix 2 for derivation
13. See appendix 3 for diagrams
**APPENDIX 1: DERIVATION OF THE SPEED OF LIGHT FROM MAXWELL’S EQUATIONS**

Given Maxwell’s basic equation

\[ \nabla \times E = \frac{\partial B}{\partial t} \quad \nabla \times B = \mu_0 \varepsilon_0 \frac{\partial E}{\partial t} \]

\[ \nabla \cdot E = 0 \quad \nabla \cdot B = 0 \]

We then compute

\[ \nabla \times (\nabla \times E) = -\frac{\partial (\nabla \times B)}{\partial t} = -\mu_0 \varepsilon_0 \frac{\partial^2}{\partial t^2} E \]

Therefore

\[ \nabla^2 E = \mu_0 \varepsilon_0 \frac{\partial^2}{\partial t^2} E \]

Using the basic definition for the energy of a wave

\[ E = E_0 \sin \left( \frac{2\pi x - vt}{\lambda} \right) \]

After differentiating the above equation we get

\[ \frac{\partial^2 E}{\partial x^2} = -E_0 \left( \frac{2\pi}{\lambda} \right)^2 \sin \left( \frac{2\pi x - vt}{\lambda} \right) \quad \text{and} \quad \frac{\partial^2 E}{\partial t^2} = -E_0 \left( \frac{2\pi}{\lambda} \right)^2 \sin \left( \frac{2\pi x - vt}{\lambda} \right) \]

Then after substituting back into our wave equation

\[ v^2 = \frac{1}{\mu_0 \varepsilon_0} \]

Therefore

\[ v = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = \frac{1}{\sqrt{(8.85418762 \times 10^{-12} \text{ m}^{-3} \text{ kg}^{-1} \text{ s}^{-1} \text{ A}^{-2}) \times (1.25663706 \times 10^{-6} \text{ m} \text{ kg} \text{ s}^2 \text{ A}^{-2})}} = 2.99792458 \times 10^8 \text{ m/s} \]

This is the exact value for the speed of light as it is know today.
APPENDIX 2: FOUCAULT’S DERIVATION OF THE SPEED OF LIGHT

The beam is focused at point $s$ on the rotating mirror, which is then directed to the fixed mirror and reflected back to $s'$ due to the mirror’s motion. From the diagram we get EQ1:

$$s_1 - s = D \cdot [ (2 \cdot \theta_1 - 2 \cdot \theta) - 2 \cdot \theta] = 2D \cdot \Delta \theta \quad (\text{EQ1})$$

This is what we see when the mirror is in motion. The image’s displacement in the beam splitter is our primary measurement, which is equated to the virtual image of the fixed mirror ($M_F$) behind the rotating mirror ($M_R$). From Optics we can determine:

$$\Delta s' = \frac{1}{o} \cdot \Delta s = \frac{A}{D + B} \cdot \Delta s \quad (\text{EQ2})$$

Where $i$ and $o$ are the distances between the image and the object from the lens, respectively.

We can then combine EQ1 and EQ2, noting that $\Delta s = S_1 - S$ (the displacement of the image), and relate this to the initial and secondary positions of the $M_R$.

$$\Delta s' = \frac{2 \cdot D \cdot A \cdot \Delta \theta}{D + B} \quad (\text{EQ3})$$

$\Delta \theta$ depends on the rotational velocity of $M_R$ and can be related to the distance the light travels, 2D:

$$\Delta \theta = \frac{2 \cdot D \cdot \omega}{c} \quad (\text{EQ4})$$

This can be combined with (EQ3) to produce:

$$\Delta s' = \frac{2 \cdot D^2 \cdot A \cdot \omega}{c \cdot (D + B)} \quad \text{This is rearranged to give the speed of light equation:}$$

$$c = \frac{2 \cdot \pi \cdot A \cdot D^2}{(D + B) \cdot (s_{cw} - s_{ccw})} \quad (\text{EQ5})$$

Where $A$ is the distance between $L_1$ and $L_2$ (minus the focal length of $L_1$), $D$ is the distance between the fixed and rotating mirrors, $\omega$ is the angular velocity of the rotating mirror, and $B$ is the distance between the rotating mirror and $i_2$.

For our purposes, this formula is rewritten as:

$$c = \frac{2 \cdot \pi \cdot A \cdot D^2 \left( \frac{Rev_{cw}}{sec} + \frac{Rev_{ccw}}{sec} \right)}{(D + B) \cdot (s_{cw} - s_{ccw})} \quad (\text{EQ6})$$

Where the abbreviations $cw$ and $ccw$ refer to clockwise and counterclockwise directions.

Here’s a sample of our results:

$$c = \frac{2 \pi (0.9305 \text{cm} - 61.73 \text{cm} - 48 \text{mm}) (11.938 \text{m})^2 \left( \frac{1503 \text{ Rev}_{cw}}{sec} + \frac{1503 \text{ Rev}_{ccw}}{sec} \right)}{(11.938 \text{m} + 0.6173 \text{m}) \left( (11.4 \text{mm}) + (11.21 \text{mm}) \right)} = 2.992 \times 10^8 \text{ m/s}$$
APPENDIX 3: DIAGRAMS

DIAGRAM 1: THE _ AND S VALUES:

Figure 2a: When $M_R$ is at angle $\theta$, the laser beam is reflected to point $S$ on $M_F$.

Figure 2b: When $M_R$ is at angle $\theta_1$, the laser beam is reflected to point $S_1$ on $M_F$.

DIAGRAM 2: THE _S AND _S` VALUES