

Experiment 1: The Speed of Light

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ABSTRACT

We have used the Foucault Method to measure the speed of light in Earth's atmosphere at approximately one atmosphere of pressure. We ran the experiment ten times to reduce the overall error in our derived value. Our best value for the speed of light is $c = 3.0 \pm 0.1 \times 10^8 \text{ m s}^{-1}$. The accepted value of the speed of light (in a vacuum) as defined by CODATA (NIST 2003) is $c = 2.99792458 \times 10^8 \text{ m s}^{-1}$. The error in our value places our derived result very close to this accepted value.

1. Introduction

The speed of light is an important value for understanding many physical phenomena in nature. Knowing the speed of light is key in determining astronomical distances, the rate of expansion and age of the Universe, as well as understanding the physical makeup of objects that we cannot physically study. Understanding the speed of light and how light interacts with matter facilitates the unlocking of mysteries of objects we cannot touch, but can observe their spectra.

The value, c , appears everywhere in physics, and is fundamental in solving a wide array of physical systems. Its significance to our understanding of the Universe cannot be overstated.

1.1. A Brief History

One of the ancient theories of vision is that light is emitted from the eye, rather than being reflected into the eye from another source. Based on this theory, the Greek engineer, Heron of Alexandria, argued that if distant objects such as stars appear immediately when one opens one's eyes, then the speed of light must be infinite (Wikipedia 2006).

The widely accepted Greek philosophy, most credited to Aristotle, was that the speed of light was infinite. However, there was an occasional challenge to this notion. For example, Empedocles of Acragas (c. 450 B.C.) insisted that light was "travelling or being at any given moment between the earth and its envelope, its movement being unobservable to us," (Ross 1931). Several other scientists supported the idea that the speed of light was finite, but had not found a way to definitively measure it. However, even renowned scientists such as Rene Descartes and Johannes Kepler supported the majority opinion that light traveled instantaneously in space, since space could offer no resistance to its motion (Kepler 1804).

In September of 1676, Danish astronomer Olaf Römer announced that a finite speed of light was responsible for the anomalous behavior of the eclipse times of Jupiter's inner moon, Io ¹. This was the first quantitative estimate of the speed of light (Wikipedia 2006). Yet, it still took more than 50 years before widespread opinion accepted that the speed of light was not infinite (Setterfield 1987).

In 1729, after James Bradley's independent confirmation of the finite value for the speed of light was published, Römer's work was finally vindicated. The scientific community finally accepted that light did not travel instantaneously (Setterfield 1987). Bradley established the finite nature of the speed of light by explaining the phenomenon known as starlight aberration. If light traveled at infinite velocity then the light from a star would appear to fall on an observer in a straight path. However, since the Earth is orbiting the sun (it is in constant motion), the observer sees a distortion of the starlight. This is because by

¹By measuring the revolution of Io while it is entering/exiting Jupiter's shadow at regular intervals, Römer calculated that Io revolved around Jupiter once every 42.5 hours when Earth was closest to Jupiter. As Earth and Jupiter moved apart, Io's exit from the shadow would begin progressively later than predicted. These exit "signals" took longer to reach Earth, as Earth and Jupiter moved further apart, as a result of the extra time it took for light to travel the extra distance between the planets, which had accumulated in the interval between one signal and the next. Similarly, Io's entries into the shadow happened more frequently, as Earth and Jupiter drew closer together. Based on these observations, Römer estimated that it would take light 22 minutes to cross the diameter of the orbit of the Earth (Wikipedia 2006).

comparing the speed of the Earth with the speed of light, the light reaches the observer at an angle. Bradley measured a deflection angle of the light to be approximately 0.02 degrees giving an approximate value for $c = 298,000 \text{ km s}^{-1}$ (Wikipedia 2006).

Hippolyte Fizeau carried out the first completely Earthbound speed of light measurement in 1849. A beam of light was incident on a mirror several thousand metres away. On the way from the source to the mirror, the beam passed through a rotating cog wheel. By knowing the rate of rotation, how far the wheel rotated on the light's path to the mirror and back, and the distance to the mirror, Fizeau was able to calculate the speed of light. He recorded a value, $c \sim 313,000 \text{ km s}^{-1}$ (Wikipedia 2006).

Several scientists repeated Fizeau's experiment making improvements along the way. Albert Michelson used variations on Fizeau's experiment on several occasions (Wikipedia 2006). In this experiment we used the Foucault Method, conceived by Léon Foucault, which improved on Fizeau's method by replacing the cogwheel with a rotating mirror. In 1862, Foucault published a value of $c \sim 298,000 \text{ km s}^{-1}$ (Wikipedia 2006).

2. The Foucault Method

Foucault's method for measuring the speed of light involves directing a beam of light at a rotating mirror. The light reflects off the rotating mirror, M_R , and is directed at a second, fixed mirror, M_F , which in turn reflects the light back along the same path back to the rotating mirror, then into a viewing scope. In the time the light traveled from M_R to M_F and back, M_R has rotated slightly. So when the beam is viewed through the scope, its image is slightly deflected. The amount of deflection of the beam of light is proportional to the time it took for the light to travel through the apparatus and back. A schematic of the Foucault apparatus used in this experiment is shown in Figure 1.

The speed of light can be determined by this method by knowing the distance the light travels, the rotation rate of the mirror, and the amount of deflection of the beam.

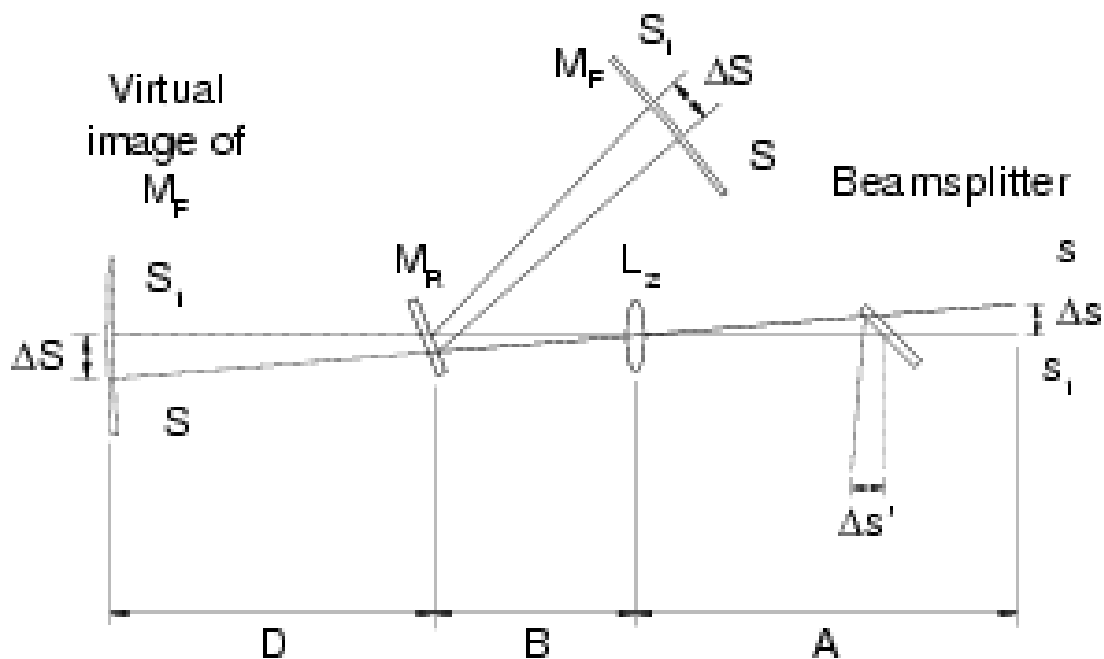


Fig. 1.— Schematic of Foucault apparatus (Pasco Scientific 1989).

3. Data Collection

Data collection for this experiment is quite simple. Simply ramp the rotating mirror up to maximum frequency in one direction, record the location of the beam in the scope along with the frequency of the mirror, run the mirror to maximum in the opposite direction and record the same parameters. So the challenge of this experiment does not arise from recording the data, it is rather in the set-up of the apparatus. If the alignment of the Foucault apparatus is not precise, data is not likely to be forthcoming at all. So considerable time must be spent in the alignment procedure.

The alignment involves first aligning the incident beam with M_R such that it is at the same height on its to and from paths. Once this alignment has been established, the next step is to align M_R with M_F such that the similar parallel path effect is achieved. Once the path of the beam has been aligned throughout the entire apparatus, the beam must be

focused by moving lens 2 (L_2) in order to focus the image of the beam in the viewing scope. A sharp focus is necessary to ensure accurate determinations of the central maximum in the point of light that appears in the scope. If the central maximum cannot be well defined, then this will cause a large degree of error in measuring the deflection of the beam, since it only deflects by a few tenth's of millimeters.

Once alignment of the apparatus was achieved, we recorded the independent parameters 10 times. These data are summarized in Tables 1 through 5. Tables 1 and 2 show the independent parameters of the apparatus that stayed constant throughout each measurement A , B , and D . Tables 3 through 5 show the independent parameters that varied experimentally with each independent measurement, ω_{CW} , ω_{CCW} , s'_{CW} , and s'_{CCW} .

Table 1. Measured Apparatus Parameters

A (m)	B (m)
0.261 ± 0.001	0.492 ± 0.001

Table 2. Measured Apparatus Parameters

D (m)
6.47 ± 0.02
8.81 ± 0.02
10.11 ± 0.02

Table 3. Experimental Data for $D = 6.47 \pm 0.02$ m

Data Set	ω_{CW}	ω_{CCW}	$s'_{CW}(\mu\text{m})$	$s'_{CCW}(\mu\text{m})$
1	1490 ± 1	1496 ± 1	195 ± 5	585 ± 5
2	1488 ± 1	1498 ± 1	190 ± 5	590 ± 5
3	1490 ± 1	1497 ± 1	190 ± 5	585 ± 5
4	1491 ± 1	1501 ± 1	190 ± 5	590 ± 5
5	1489 ± 1	1499 ± 1	193 ± 5	595 ± 5
6	1493 ± 1	1500 ± 1	193 ± 5	586 ± 5
7	1488 ± 1	1499 ± 1	191 ± 5	590 ± 5
8	1489 ± 1	1498 ± 1	190 ± 5	591 ± 5
9	1486 ± 1	1502 ± 1	192 ± 5	591 ± 5
10	1492 ± 1	1501 ± 1	193 ± 5	593 ± 5

Table 4. Experimental Data for $D = 8.81 \pm 0.02$ m

Data Set	ω_{CW}	ω_{CCW}	$s'_{CW}(\mu\text{m})$	$s'_{CCW}(\mu\text{m})$
1	1492 ± 1	1504 ± 1	150 ± 5	695 ± 5
2	1489 ± 1	1500 ± 1	142 ± 5	696 ± 5
3	1491 ± 1	1505 ± 1	140 ± 5	692 ± 5
4	1489 ± 1	1500 ± 1	142 ± 5	695 ± 5
5	1492 ± 1	1504 ± 1	143 ± 5	696 ± 5
6	1498 ± 1	1503 ± 1	139 ± 5	695 ± 5
7	1494 ± 1	1505 ± 1	143 ± 5	696 ± 5
8	1494 ± 1	1504 ± 1	144 ± 5	695 ± 5
9	1491 ± 1	1503 ± 1	142 ± 5	689 ± 5
10	1495 ± 1	1505 ± 1	142 ± 5	699 ± 5

Table 5. Experimental Data for $D = 10.11 \pm 0.02$ m

Data Set	ω_{CW}	ω_{CCW}	$s'_{CW}(\mu\text{m})$	$s'_{CCW}(\mu\text{m})$
1	1487 ± 1	1503 ± 1	85 ± 5	705 ± 5
2	1492 ± 1	1504 ± 1	75 ± 5	705 ± 5
3	1492 ± 1	1505 ± 1	80 ± 5	705 ± 5
4	1491 ± 1	1501 ± 1	71 ± 5	700 ± 5
5	1490 ± 1	1502 ± 1	73 ± 5	698 ± 5
6	1487 ± 1	1501 ± 1	84 ± 5	710 ± 5
7	1489 ± 1	1501 ± 1	79 ± 5	705 ± 5
8	1489 ± 1	1501 ± 1	72 ± 5	701 ± 5
9	1489 ± 1	1499 ± 1	71 ± 5	700 ± 5
10	1486 ± 1	1503 ± 1	80 ± 5	700 ± 5

4. Data Analysis

The speed of light, c , can be determined with the measured independent parameters by the following formula:

$$c = \frac{8\pi AD^2(\omega_{CW} - \omega_{CCW})}{(D + B)(s'_{CCW} - s'_{CW})}, \quad (1)$$

where A is the distance between L_2 and L_1 , minus the focal length of L_1 , D is the distance between M_R and M_F , B is the distance between L_2 and M_R , ω_{CW} and ω_{CCW} are the clockwise and counter-clockwise angular frequencies of M_R , respectively, and s'_{CW} and s'_{CCW} are the respective clockwise and counter-clockwise deflections of the light beam (see Figure 1)(Pasco Scientific 1989).

4.1. Error Analysis

There are five independent variables in the calculation of c (see Eq. 1), each with its own error in measurement. Thus, to calculate the total error in the derived value for c , standard error propagation techniques must be used. The standard deviation of a calculated quantity based on independent variables, each with its own associated error is defined by

$$\sigma_n^2 = \sum_i \left(\frac{\partial c}{\partial x_i} \right)^2 \sigma_{x_i}^2, \quad (2)$$

where x_i are the independent measured parameters – A , B , D , ω_{CW} , ω_{CCW} , s'_{CW} , and s'_{CCW} – used to calculate c . A , B , and D , also have errors propagated through them defined by equation (2), because they are calculated by the measured locations of components of the apparatus. Ten measurements were used to determine c , so we can define the error in the mean by

$$\sigma_c^2 = \frac{1}{N-1} \sum_{i=1}^N (c_i - \bar{c})^2, \quad (3)$$

where N is the number of measured data points, c_i is the value of c calculated for each set of data, and \bar{c} is the average value of c . The reduced standard error, or RMS deviation is

then

$$S_c = \frac{1}{\sqrt{N}} \sigma_c . \quad (4)$$

5. Results

Our best result for the speed of light is $c = 3.0 \pm 0.1 \times 10^8 \text{ m s}^{-1}$. The results for each data set are summarized in Tables 6 through 8. This is relatively close to the modern accepted value² of the speed of light in a vacuum, $c = 2.99792458 \times 10^8 \text{ m s}^{-1}$ (NIST 2003).

²This value of c is recommended for international use by CODATA and is the latest available. From "2002 CODATA recommended values," it is generally recognized worldwide for use in all fields of science and technology (NIST 2003).

Table 6. Derived c Results ($D = 6.47 \pm 0.02$ m)

Data Set	c (10^8 m s $^{-1}$)
1	3.0 ± 0.1
2	2.9 ± 0.1
3	3.0 ± 0.1
4	2.9 ± 0.1
5	2.9 ± 0.1
6	3.0 ± 0.1
7	3.0 ± 0.1
8	2.9 ± 0.1
9	2.9 ± 0.1
10	3.0 ± 0.1
Average	3.0 ± 0.1

Table 7. Derived c Results ($D = 8.81 \pm 0.02$ m)

Data Set	c (10^8 m s $^{-1}$)
1	3.0 ± 0.1
2	2.9 ± 0.1
3	3.0 ± 0.1
4	3.0 ± 0.1
5	3.0 ± 0.1
6	2.9 ± 0.1
7	3.0 ± 0.1
8	3.0 ± 0.1
9	2.9 ± 0.1
10	3.0 ± 0.1
Average	3.0 ± 0.1

Table 8. Derived c Results ($D = 10.11 \pm 0.02$ m)

Data Set	c (10^8 m s $^{-1}$)
1	3.0 ± 0.1
2	2.9 ± 0.1
3	3.0 ± 0.1
4	2.9 ± 0.1
5	2.9 ± 0.1
6	3.0 ± 0.1
7	3.0 ± 0.1
8	2.9 ± 0.1
9	2.9 ± 0.1
10	3.0 ± 0.1
Average	3.0 ± 0.1

6. Conclusions & Discussion

The Foucault method, an improvement on the Fizeau method, is a very interesting way to measure the speed of light. It provides good results with a few basic instruments. The determination of c with this method can be challenging, as the apparatus requires precise alignment, and a well focused beam. The experiment may be improved by using a larger separation between M_R and M_F , because this will give a larger beam deflection as the mirror will have rotated farther on the light's path from M_R to M_F and back. A larger measurement in overall deflection will reduce the overall error in this value, and hence in the calculated value of c .

This experiment was key in determining the value of a constant that is used to understand many types of physical phenomena. If c were infinite, as was widely accepted in times past, most physical phenomena involving the transfer of information would be chaotic at best to understand. However, understanding the finite nature of light has unlocked mysteries about how information is transferred, and has been key in unlocking the history of our Universe.

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