Determination of the Speed of Light using a direct and indirect method

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1 Abstract

The speed of light was found directly by moving a transmitted laser various distances from a reference laser and measuring the resulting time difference between their peaks. Using this method the speed of light was found to be $(2.43 \pm 0.40) \times 10^8 ms^{-1}$ which is consistent with the published value to within three errors. The speed of light was found indirectly by determining the magnetic permeability and electric permittivity of free space. The magnetic permeability was determined with a simple current balance using a digital mass scale to measure the electromagnetic repulsion between two rods caused by various currents. The electric permittivity of free-space was determined using a parallel-plate capacitor to measure the voltage at which different thicknesses of foil lifted off the capacitor plate. Using this method the speed of light was found indirectly to be $(2.58 \pm 0.58) \times 10^8 ms^{-1}$ which is consistent with the direct value and the published value to within one error.

2 Introduction

Measuring the speed of light accurately has been the subject of scientific endeavour for centuries. The speed of light is used to measure distances in space, over such large distances a small error in the speed of light results in massive errors in the distance to stars. It is used to define distance, with 1 meter being the distance light travels in a second. The speed of light is also important in other areas of physics, primarily Einstein's second postulate which considers the speed of light in a vacuum to be the same in all inertial frames and revolutionised physics in 1905 with the development of special relativity. Einstein's famous mass-energy relation, $E = mc^2$ for an object at rest allowed mass m and energy E to be considered interchangeable. This has huge implications, for example by explaining how energy can be produced by nuclear fusion and nuclear fission.[1]

The main aim of this experiment was to measure the speed of light as accurately as possible using a direct method. This was compared with a less accurate, order-of-magnitude estimate obtained using an indirect method.

For many centuries, there was much debate as to whether the speed of light was infinite. Danish Astronomer, Ole Rømer was the first to calculate the speed of light by observing the eclipses of Jupiter's moon, Io. There was a discrepancy in the time between eclipses, increasing when the Earth moves away from Jupiter and decreasing when it moves towards Jupiter. Rømer interpreted this as the time it takes for light to travel between Earth and Jupiter and found the speed of light to be $2.14 \times 10^8 ms^{-1}$ which is of the same order of magnitude as the current value and very accurate considering the technology available at the time.[2] [3]

Today, much more accurate measurements of the speed of light can be achieved with lasers. Evenson et al measured the speed of light using laser interferometry to be $(299792456.2 \pm 1.1)ms^{-1}$ The speed of light in a vacuum is now fixed at $299792458ms^{-1}$ and used to define the meter.[4]

By considering light to be an electromagnetic wave, Maxwell's equations allowed the speed of light to be theoretically calculated using the following equation,

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} \tag{1}$$

where c is the speed of light in a vacuum, μ_0 is the magnetic permeability of free-space in Hm^{-1} and ϵ_0 is the electric permittivity of free-space in Fm^{-1}.[5]

3 Theory

3.1 Direct Method

The speed of light was found directly using the Leybold 476 301 didatic equipment. The Leybold apparatus outputs two signals, a reference signal that goes straight to the in-built photodiode and a transmitted signal that can be moved. The transmitter can be placed a certain distance from the photodiode and calibrated to be in-phase with the reference signal using the phase-shifter. The transmitter is then moved various distances, Δs, from this calibration point causing the transmitted signal to be out of phase with the reference signal by a time Δt. The displacement and time-shift are related by the following equation,

$$\Delta t = \frac{\Delta s}{c} T v \tag{2}$$

where v is the modulation frequency which is known. Hence, a graph can be plotted of the time-shift against the displacement and the gradient of this graph can be used to determine the speed of light in air since this graph is a straight-line in the form $y = mx$.[6]

3.2 Magnetic Permeability

A mass-scale was used as a current-balance to measure the magnetic permeability. A wooden-block attached to a rod was placed on a mass-scale which was zeroed. A second rod was placed above this rod and currents were passed through the rods in opposite directions so that the rods would experience electromagnetic repulsion. The mass-scale would then display a reading directly proportional to the electromagnetic repulsion given by,

$$mg = \frac{L I_1 I_2 \mu_0}{2\pi r} \tag{3}$$

where m is the mass reading, g is the constant of proportionality/acceleration due to gravity, L is the length of the rods, I_1 is the current passing through the rod attached to the block, I_2 is the current passing through the second rod, and r is the separation between the two rods.

This can be re-arranged into the following form, using the fact that the current passing through each rod is equal but in opposite directions,

$$m = \frac{L\mu_0}{2\pi r g} I^2 \tag{4}$$

hence a graph of the mass-reading against the current squared can be plotted. The graph will be a straight-line in the form $y = mx$ so the gradient of the graph can be calculated and used to determine the magnetic permeability of free-space.[8]

3.3 Electric Permitivitty

The speed of light can be found indirectly by measuring the magnetic permeability and electric permittivity of free-space and using equation 1.

A parallel-plate capacitor was constructed and used to determine the electric permitivitty by measuring the voltages at which pieces of foil of known mass lifted up. At this voltage, the gravitational force was balanced by the electric force, leading to the following equation

$$\frac{\epsilon_0 v^2 A}{2d^2} = \rho A t g \tag{5}$$

where v is the voltage at which the foil lifts up, A is the surface-area of the foil, d is the plate seperation, t is the thickness of the foil and g is the acceleration due to gravity.

This can be re-arranged into the following form,

$$v^2 = \frac{2d^2 \rho g}{\epsilon_0} t \tag{6}$$

hence a graph of voltage-squared against thickness of foil can be plotted. The graph will be a straight line of the form $y = mx$ so the gradient of the graph can be used to determine the electric permitivitty of free-space.[7]

3.4 Refractive Index

Light is an electromagnetic wave consisting of transverse, oscillating electric and magnetic fields. When light travels through a medium that is not a vacumn it causes electrons in the medium to also move and emit electromagnetic waves that interact with the light. The combined wave is slower so the light has effectively been slowed down by the medium. If light enters the medium at an angle one side of the wavefront is slowed before the other so the angle of the light is changed in a phenomenom called refraction. The amount light is slowed down in the medium depends on the refractive index of the medium, n, given by,

$$n = \frac{c_0}{v} \tag{7}$$

where c_0 is the speed of light in a vacumn and v is the speed of light in the medium. [10]

The Leybold 476 301 didatic equipment can also be used to measure the refractive index of various mediums using the following equation,

$$n = 1 + \frac{c_0 t}{d v T} \tag{8}$$

where n is the refractive index, c_0 is the speed of light in a vacuum, t is the time difference due to light slowing down in the medium, d is the length of the medium, v is the modulation frequency and T is the time period of the reference signal.[9]

Figure 1: Leybold Apparatus Block Diagram

4 Experimental Procedure

4.1 Direct Method

We set up the Leybold apparatus as shown below and connected it to an oscilloscope so the transmitted signal appeared on CH1 and the reference signal on CH2.

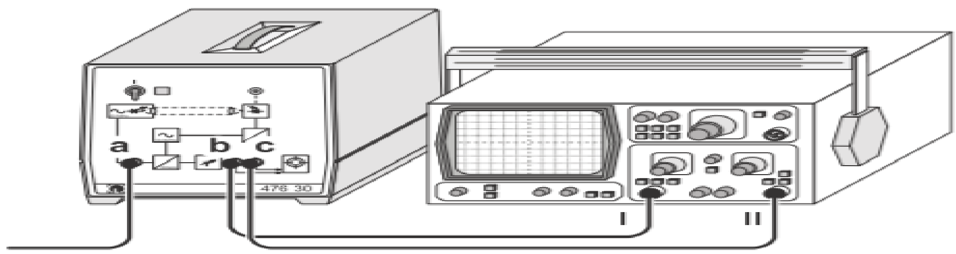

Figure 2: Leybold Oscilloscope Connection

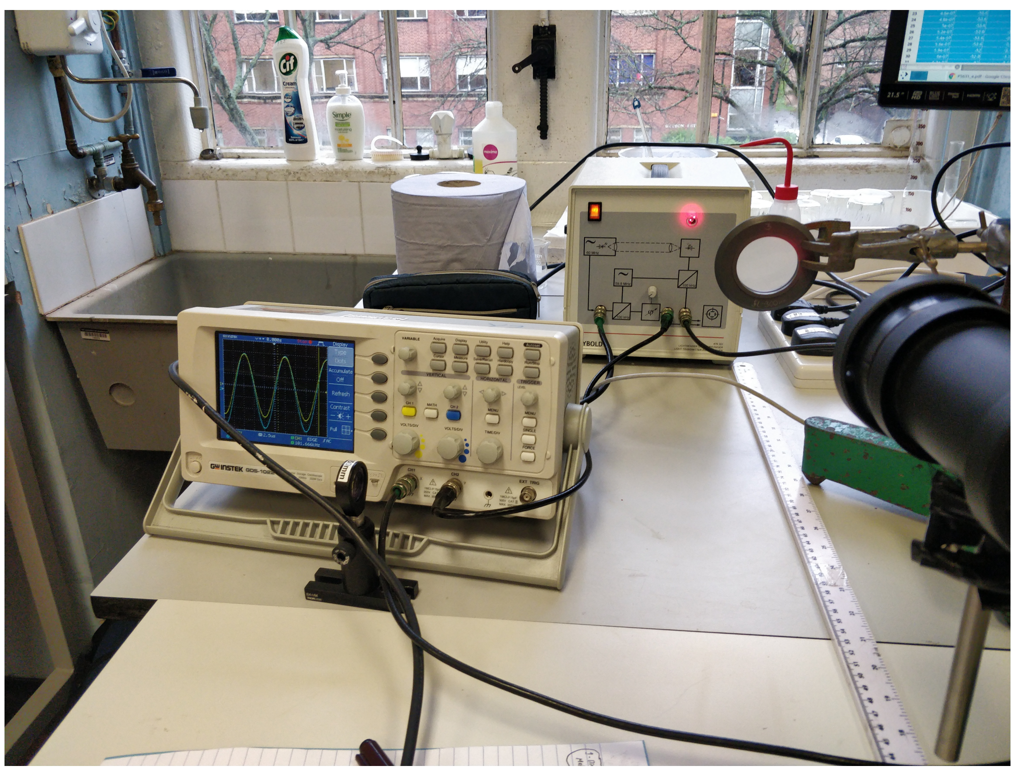

Figure 3: Leybold Apparatus Set-up

The transmitter was moved to the calibration point (50.0 ± 0.1) cm from the photodiode. A meter ruler was used to measure distances. A 300mm focal length lens was placed in between the transmitter and photodiode and the position of the lens and transmitter was adjusted so as to maximise the light incident on the photodiode i.e. CH1 on the oscilloscope. The phase-shifter was adjusted to ensure the transmitted and reference signal were in-phase. Data from the oscilloscope was captured using the scopedope program and copied into the LeyboldData spreadsheet. Below is the graph of the calibrated reference and transmitted signals.

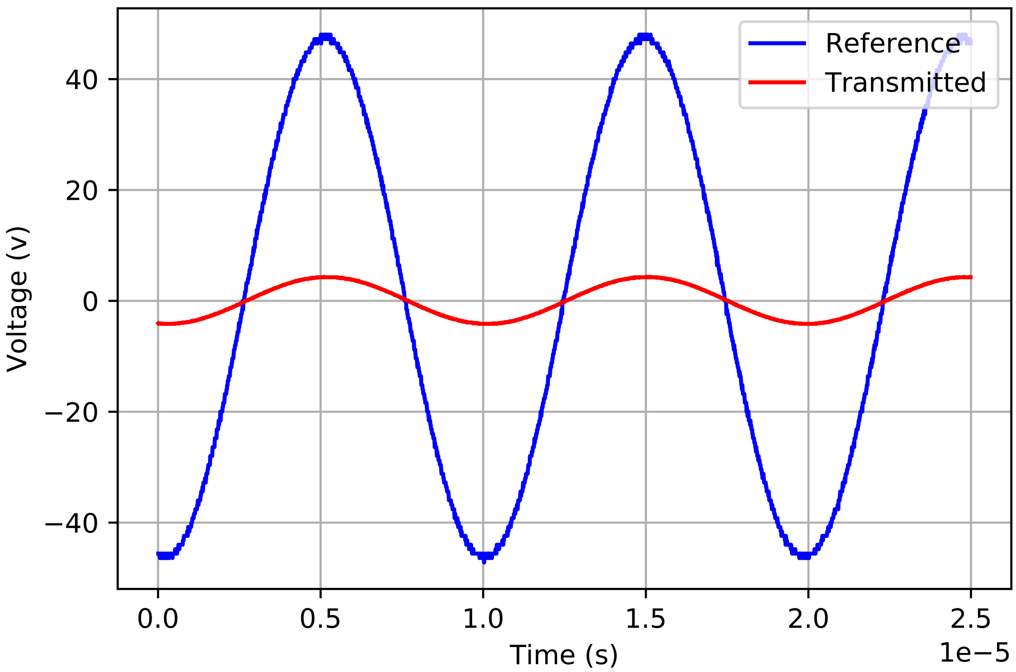

Figure 4: Calibrated Signal

The transmitter was then moved distances of $(0.500 \pm 0.001)m, (1.000 \pm 0.001)m, (1.500 \pm 0.002)m, (1.750 \pm 0.002)m, (2.000 \pm 0.002)m, (2.500 \pm 0.003)m, (3.200 \pm 0.004)m$ from the calibration point. For each distance we used scopedump to copy data of the transmitted and reference signals into different tabs in the LeyboldData spreadsheet. We ensured the lens and transmitter were aligned to maximise the light incident on the photodiode at each distance.

4.2 Magnetic Permeability

We set-up the magnetic permeability apparatus as shown in the diagram below. A wooden block was placed on the weighing scale and a copper rod was glued to the block. We measured the length of the rod to be $L = (9.0 \pm 0.1)$cm. We drilled a hole in two wooden blocks, placed them either side of the scale and inserted a second rod into them parallel to the first rod. The separation between the rods was $r = (5 \pm 1)$mm.

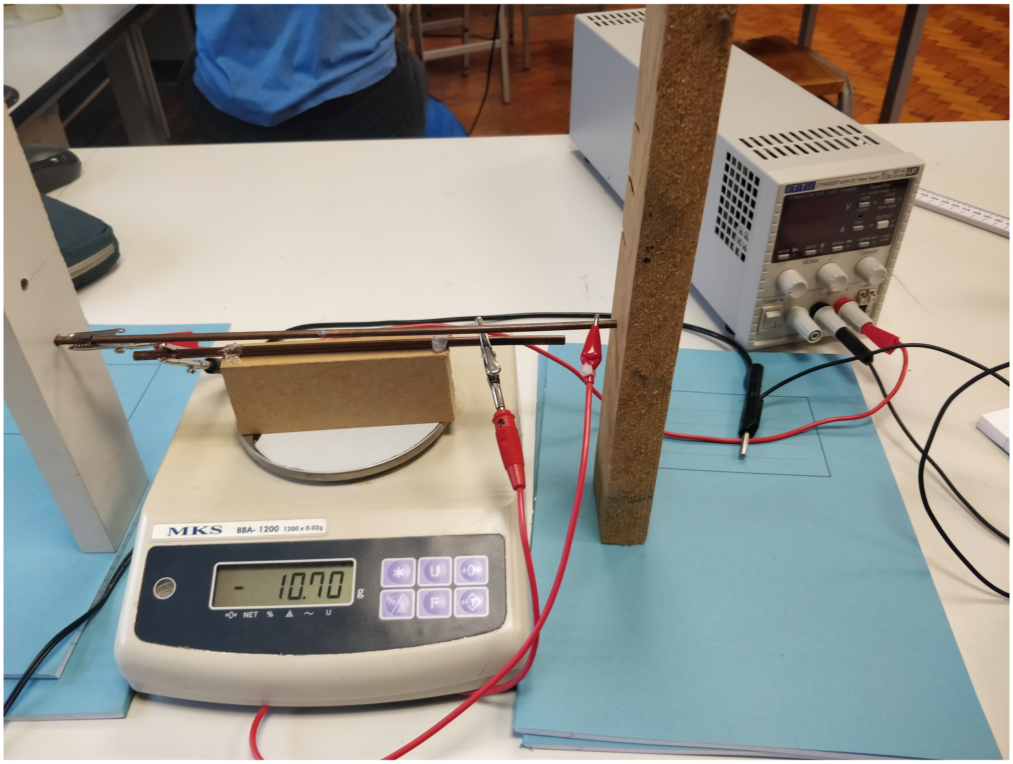

Figure 5: Magnetic Permeability Experimental Set-up

We passed currents of $(20.00 \pm 0.01)A$, $(19.00 \pm 0.01)A$, (18.00 ± 0.01), (16.00 ± 0.01), $(14.00 \pm 0.01)A$, $(12.00 \pm 0.01)A$ through the rods. We had difficulty getting a mass reading so had to turn the power supply off quickly and measure the reading quickly before it decreased. This was repeated 5 times for each current to get a mean mass.

4.3 Electric Permitivitty

We prepared foil with 5 different thicknesses by folding the foil up to 4 times. The unfolded foil was too thin to measure using vernier callipers so we measured the thickness of the foil after being folded twice to be $t = (0.21 \pm 0.05)$mm. We used this to calculate the thickness and error in the thickness for the other pieces of foil. The error in the thickness of the foil was quite large at 24% to 2 s.f.

We initially constructed our capacitor using two steel washers separated by strips of perf-board wrapped in electrical tape. Thin wire was soldered to each washer and connected to the output terminals of a high voltage power supply.

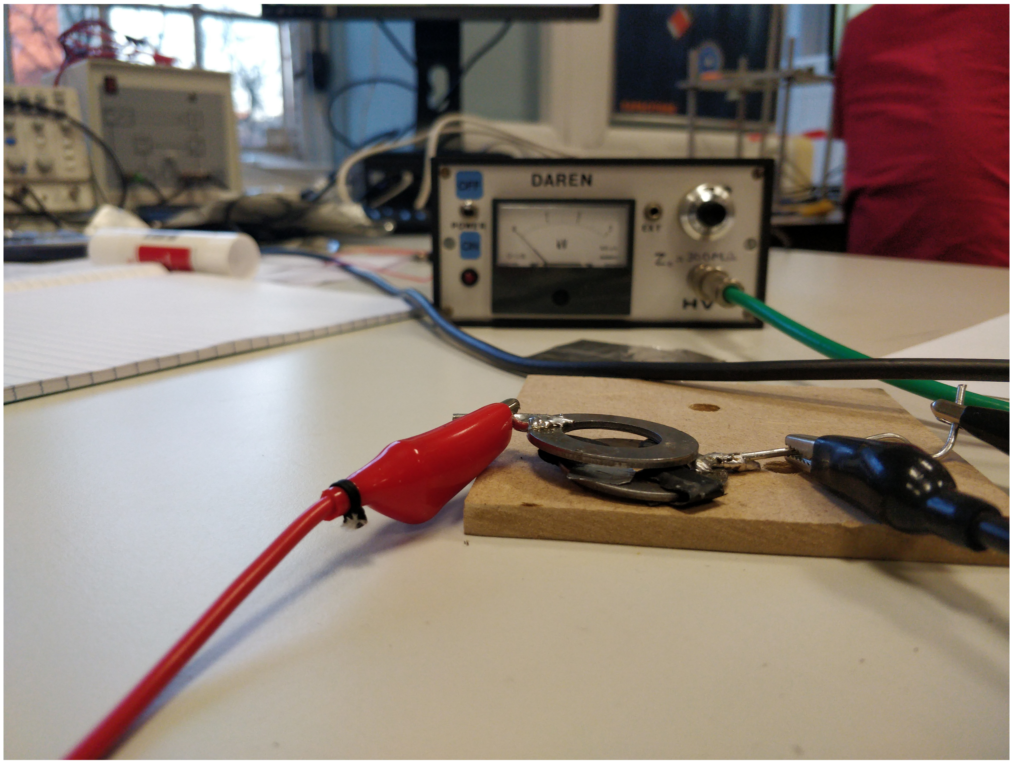

Figure 6: Electric Permitivitty Initial Set-up

We performed a preliminary run using the foil with thickness $t = (0.14 \pm 0.033)$mm but had difficulty getting consistent voltages at which the foil lifted up. Due to the capacitor itself being small it was hard to see the foil and determine at what voltage it lifted. Connecting wires to the washers also exerted torque on the washers and made it hard to keep the washers flat and parallel to each other, which is important since the distance between the two washers is assumed to be constant in equation 6.

We later decided to replace the capacitor with two much larger (8.0 ± 0.1)cm by (8.0 ± 0.1)cm metal plates. This allowed bigger pieces of foil to be used and overcame some of the problems we encountered earlier. The two metal plates were separated by perfboard wrapped in electrical tape. The separation between the two plates was measured using vernier calipers 5 times along the length of the capacitor.The average separation was calculated to be $d = (2.22 \pm 0.35)$mm.

Since the density of the foil was not given we had to determine the density of foil using the following equation,

$$\rho = \frac{m}{thw} \tag{9}$$

where h is the height of the foil, and w is the width. A large piece of foil was used to lower the uncertainty in the density. The width, height and thickness of the foil was measured to be (26.5 ± 0.1)cm, (37.2 ± 0.1)cm, and (0.07 ± 0.017)mm respectively. The mass of the foil was measured using ACB Plus 300 digital weighing scales to be (4.75 ± 0.01)g. This gave a density of $690 \pm 170)$kgm^{-3}.

We measured the voltage at which each of the 5 pieces of foil started to lift up 5 times to calculate an average for piece of foil. The results are in the PermitivittyData spreadsheet. Below is the set-up for the square-plate capacitor.

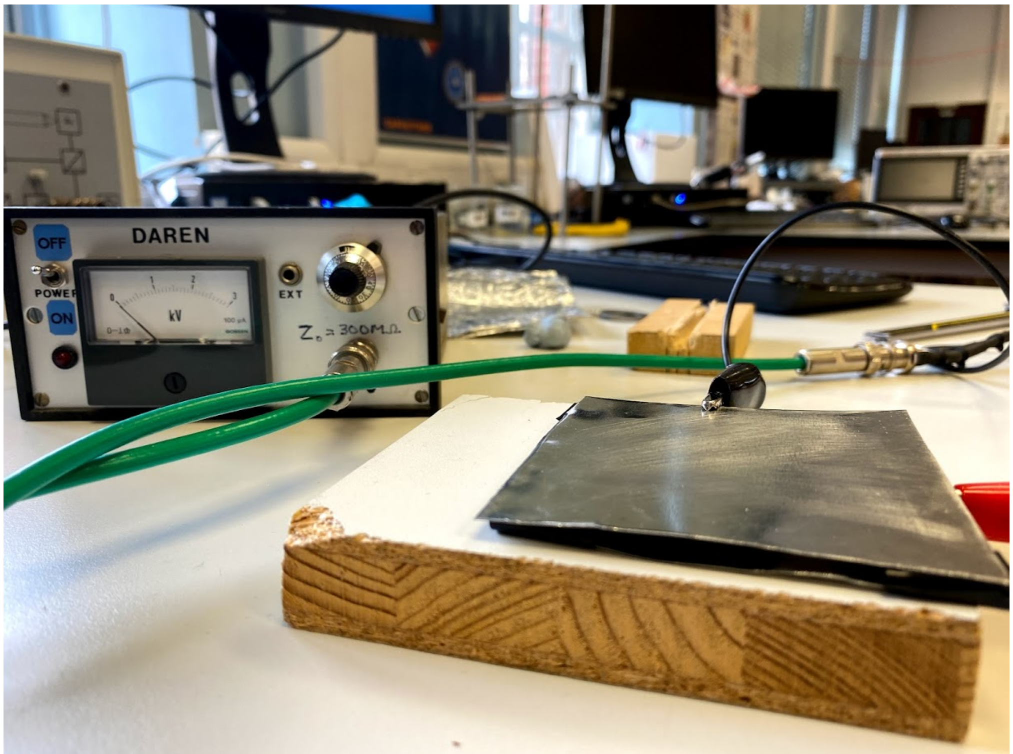

Figure 7: Electric Permitivitty Experimental Set-up

4.4 Refractive Index

We then set out measuring the refractive index of water and a plastic rod. We cleaned a plastic tank and measured its dimensions before filling it with water. The wall thickness was measured using vernier calipers and the length was measured with measuring tape.
Wall 1 thickness = (9.71 ± 0.01)mm
Wall 2 thickness = $(9.77 \pm 0.01$mm
Length including 2 walls = (52.00 ± 0.05)
Length of water $L = 50.05 \pm 0.05)$
Total wall thickness $(t_1 = (19.48 \pm 0.02)$mm

The box was then orientated horizontally and its dimensions were measured. Wall 1 thickness = (9.72 ± 0.01)mm
Wall 2 thickness = (9.78 ± 0.01)mm
Total Wall thickness $t_2 = (19.50 \pm 0.02)$mm
Box width including 2 walls=(21.50 ± 0.05)cm

Box with not including two walls $w = (19.55 \pm 0.05)$cm

The transmitter was moved to the reference point (50.0 ± 0.1)cm from the photodiode and calibrated to ensure the reference and transmitted signals were in phase.

The tank was then filled with water and placed with its front-edge on the reference point and the transmitter pushed against its back edge so the laser would travel through only the box of water before getting to the reference point. The laser was refracted quite significantly by the water so we had to elevate the transmitter and box of water relative to the photodiode to ensure the laser reached the photodiode. Data from the oscilloscope was captured using scopedump and copied into the DataMaterials spreadsheet.

Since the rod was being investigated on a different day the reference and transmitted signals were re-calibrated. The length of the acrylic rod was measured to be $d = (65.0 \pm 0.1)cm$. The rod was placed with its front edge level with the calibration point and its back edge pushed against the transmitter. The transmitted and reference signal were then measured for the rod, empty box and air (by removing the empty box)

5 Results and Interpretation

5.1 Direct Method

To find the speed of light using equation 2, the time difference for each distance needed to be calculated. The most accurate way of determining the time difference was to model the transmitted and reference signal to a sinusoidal function since this eliminated any human error finding the peak values. The voltage can also be extrapolated between time measurements by the oscilloscope so peaks can be found more accurately than using only the raw data. The sinusodial function is given by,

$$y = Acos(\frac{2\pi}{T}x + \sigma) \tag{10}$$

where y is the voltage, A is the amplitude of the wave, T is the time-period of the wave, x is the time, and σ is the offset. The data was modelled to equation 10 using scipy.optimize.leastsq which minimised the difference between the fitted function and the data by changing the values of the parameters using least-squares fitting. The peak of the transmitted and reference signals was found by differentiating each fitted function using sympy.diff and finding out the x value where the derivative was equal to 0 by solving the derviative for x with sympy.solve. The time difference was then found by subtracting the transmitted and reference peak.

To ensure the correct time difference was found the program ensured that the following conditions were met:

1. The peak corresponded to a maximum point not a minimum point

2. The peak x value is positive, since the domain of equation 10 includes both positive and negative numbers but the actual data from the oscilloscope includes only positive values for time

3. The transmitted signal peak should appear after the reference signal peak

If a peak was found not satisfying these conditions the program would move to the next peak by moving half a cycle/time period forward until these conditions were all met. The code for finding the transmitted peak is shown below:

```
idx = 0
    while tran_eqn_solution_2 < 0 or tran_peak_2 < 0 or tran_peak_2 < ref_peak_2:
        tran_peak_2 = tran_peak_2 + 0.5*ptran[1]
        tran_eqn_solution_2 = tran_eqn.subs(x,tran_peak_2)

        if idx>4:
            break

        idx+=1
```

The time period, T, and calibration time difference T_c was found using this method on the reference and transmitted signals from the reference point, shown in the following figure.

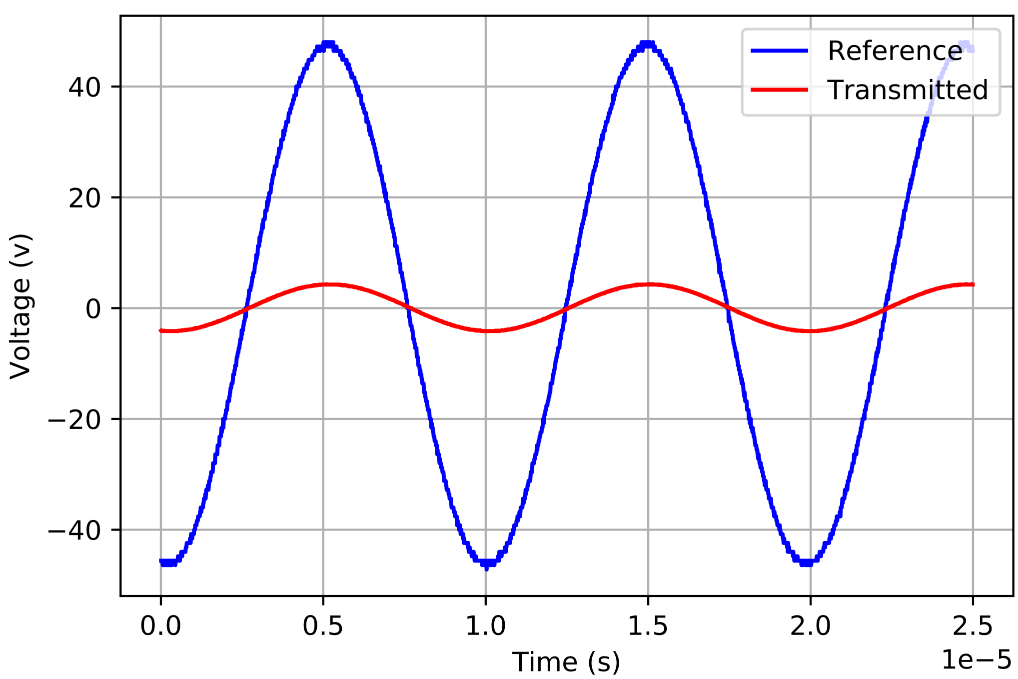

Figure 8: Time Period

As seen in figure 8, a very good fit was found for the reference and transmitted signals with R^2 values of 0.995 to 3 significant figures for each. The reference and transmitted signals were not exactly in phase as the calibration time difference between their peaks was $T_c = (1.6 \pm 0.2) \times 10^{-7} s$. This calibration time difference is a source of systematic error that can be eliminated by subtracting the calibration time difference from the time difference for each distance. The time period was found using the least squares fit of the reference signal to be $T = (9.833 \pm 0.001) \times 10^{-6} s$.

The time difference Δt was found for each distance Δs using this method. The data is shown in the table below.

Table 1: Time Differences for various Distances

Distance (m)	**Time Difference (10^{-6} s)**
0.500 ± 0.001	1.0953 ± 0.0048
1.000 ± 0.001	2.3430 ± 0.0049
1.500 ± 0.002	0.0764 ± 0.0029
1.750 ± 0.002	7.9759 ± 0.0329
2.000 ± 0.002	4.5809 ± 0.0046
2.500 ± 0.003	5.501 ± 0.0051
3.200 ± 0.004	8.6360 ± 0.0182

The time difference and distance data was fitted to equation 2 using an ordinary least squares fit with statsmodel.api.OLS. The fit is shown below.

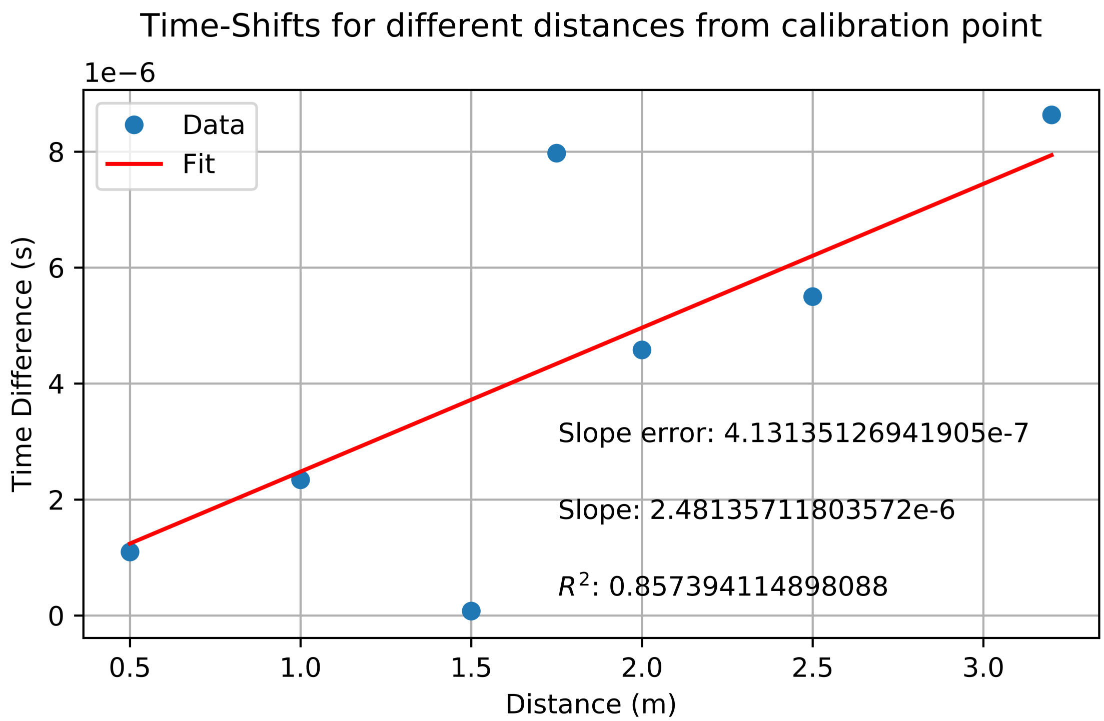

Figure 9: Graph of time difference against path difference

There was a clear positive correlation between the time difference and distance as predicted by equation 2. However, the presence of an outlier for the third and fourth data point resulted in a lower R^2 value of 0.857 to 3 significant figures. The gradient of figure 9 was calculated to be $m = (2.5 \pm 0.4) s m^{-1}$.

Finally the speed of light was found directly using the following re-arranged form of equation 2

$$c = \frac{\Delta S}{\Delta t} T v \tag{11}$$

Using the fact that the gradient of 9 is $m = \frac{\Delta t}{\Delta s}$ this becomes

$$c = \frac{T v n}{m} \tag{12}$$

where n is the refractive index of air. The modulation frequency was given by Leybold to be $v = (60.000 \pm 0.005) \times 10^6 Hz/$. The speed of light was calculated using equation 12 to be $c = (2.43 \pm 0.40) \times 10^8 m s^{-1}$ which is consistent with the published value to within three errors.

5.2 Magnetic Permeability

Below is the mean mass reading for different currents.

Table 2: Magnetic Permeability Data

Current (A)	Current Squared (A^2)	Mean Mass
20.00 ± 0.01	400 .0 ± 0.4	1.50 ± 0.10
19.02 ± 0.01	361.8 ± 0.4	1.48 ± 0.10
18.01 ± 0.01	324.4 ± 0.4	1.20 ± 0.10
15.98 ± 0.01	255.4 ±0.3	1.04 ± 0.10
14.01 ± 0.01	196.3 ± 0.3	0.80 ± 0.10
12.00 ± 0.01	144 ± 0.2	0.68 ± 0.10

The current squared and mean mass data was fitted to equation 4 using an ordinary least squares fit with statsmodel.api.OLS. The fit is shown below.

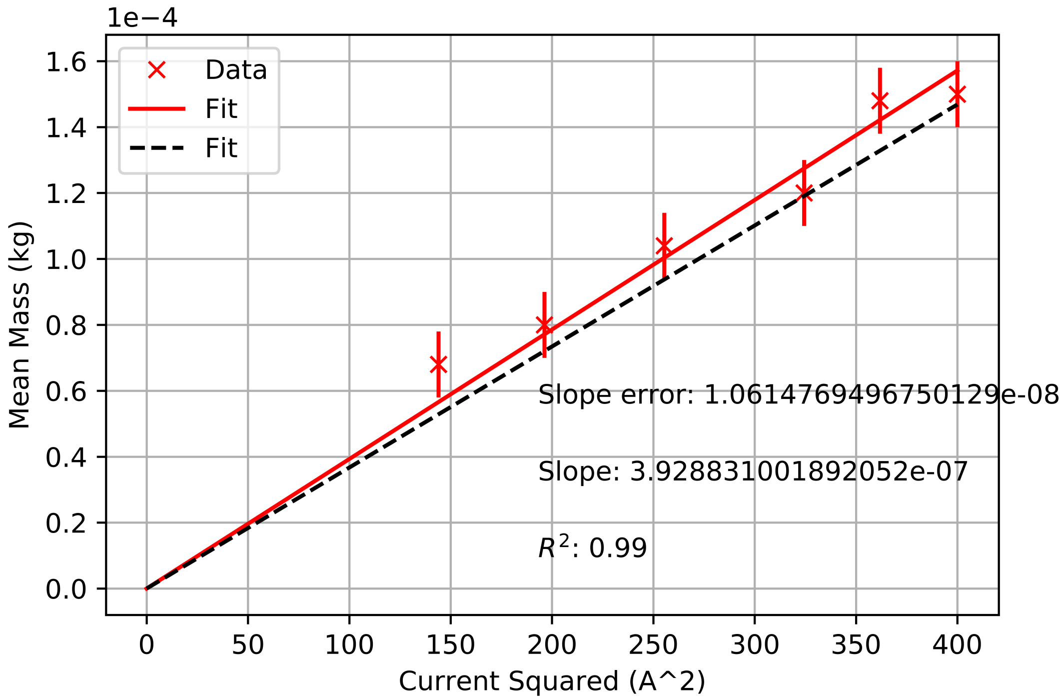

Figure 10: Graph of mass against current squared

As seen from figure 10, the fit modelled the data well with a high R^2 value of 0.99 and a clear positive correlation between the mean mass and current squared. The experimental mass data matched fairly well with the theoretical mass data using the published value of μ_0 to calculate the mass from equation 4. However the discrepancy between the theoretical and experimental mass data increased for larger masses/currents.

The gradient was calculated to be $M = (3.9 \pm 0.1) \times 10^{-7} kgA^{-2}$. Using the fact that $M = m/I^2$ this was substituted into equation 4 to give,

$$\mu_0 = \frac{2\pi r M g}{L} \tag{13}$$

leading to value of the magnetic permeability of free-space of $\mu_0 = (1.35 \pm 0.27) \times 10^{-6} Hm^{-1}$ which is consistent with the published value to within one error.

5.3 Electric Permitvitty

Below is the mean voltage squared for each foil thickness.

Table 3: Magnetic Permeability Data

Foil Thickness (x10^{-4}m)	Mean Voltage (V)	Mean Voltage Squared (x10^6 V^2)
0.7 ± 0.2	775 ± 50	0.60 ± 0.08
1.4 ± 0.3	1120 ± 50	1.25 ± 0.11
2.1 ± 0.5	1310 ± 50	1.72 ± 0.13
2.8 ± 0.7	1518 ± 50	2.30 ± 0.15
3.5 ± 0.8	1270 ± 50	1.61 ± 0.13
4.2 ± 1.0	1300 ± 50	1.69 ± 0.13

The foil thickness and mean voltage squared data was fitted to equation 6 using an ordinary least squares fit with statsmodel.api.OLS. The fit is shown below.

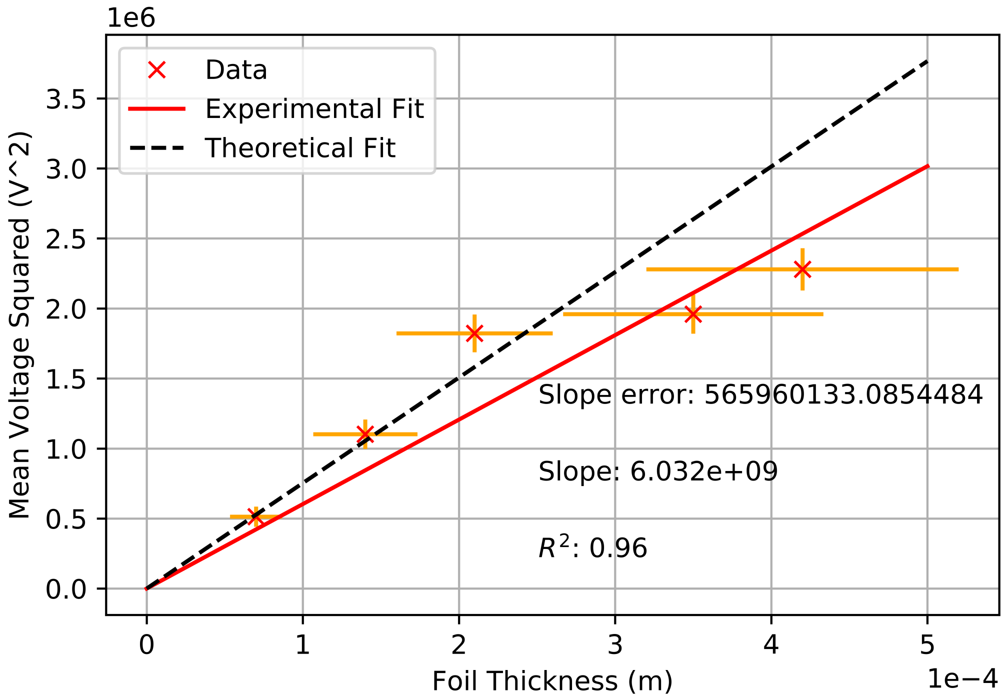

Figure 11: Graph of Voltage Squared against foil thickness

As seen from figure 11, the fit modelled the data well with a high R^2 value of 0.96 and a clear positive correlation between the mean voltage squared and foil thickness. There was quite a significant discrepancy between the experimental mean voltage squared and the theoretical voltage squared calculated using the published value of ϵ_0 and equation 6. This discrepancy increased for larger foil thicknesses.

There was a large uncertainty for the foil thickness as seen by the large error bars in figure 11 and errors in table 3. This was because the foil thickness was measured only for the foil folded twice (the third data point). The other foil thicknesses were calculated from this value.

The gradient was calculated to be $m = (6.03 \pm 0.57) \times 10^9 V^2 m^{-1}$. Using the fact that $m = v^2/t$ this was substituted into equation 6 to give,

$$\epsilon_0 = \frac{2d^2 \rho g}{m} \tag{14}$$

leading to a value of the electric permitivitty of free-space of $\epsilon_0 = (1.11 \pm 0.45) \times 10^{-11} F m^{-1}$ which is consistent with the published value to within one error.

5.4 Refractive Index

The time difference for the different materials was calculated in the same way as in section 5.1. The data is shown below.

Table 4: Time Differences Materials

Material	Distance (m)	Time difference ($x10^{-6}$ s)
Air	0.520 ± 0.001	1.048 ± 0.005
Empty Box	0.520 ± 0.001	1.114 ± 0.005
Acrylic Rod	0.650 ± 0.001	1.533 ± 0.006
Box filled with water	0.501 ± 0.001	1.500± 0.005
Box filled with water	0.196 ± 0.001	8.139 ± 0.005

The data was collected over two days and each day the transmitter was moved to the calibration point and adjusted to be in phase with the reference signal.

The time period and calibration time difference for the first day were calculated to be $T_2 = (9.8291 \pm 0.0008) \times 10^{-6}s$ and $T_{c2} = (7.3 \pm 0.2) \times 10^{-8}s$ respectively. The calibration time difference, T_{c2}, was subtracted from the initial time differences for the box filled with water.

The time period and calibration time difference for the second day was calculated to be $T_1 = (9.8253 \pm 0.0006) \times 10^{-6}s$ and $T_{c1} = (9.2 \pm 0.3) \times 10^{-8}s$ respectively. The calibration time difference, T_{c1}, was subtracted from the initial time differences for air, the empty box and plastic rod.

The time differences also needed to be corrected to eliminate the time difference caused by the transmitter being a distance, d, away from the calibration point. Eliminating this source of time difference will mean the time differences are only due to the refractive index of the medium the light travels through.

The time difference for air was used in the following equation to find the rate of change of time difference with respect to distance,m,

$$m = \frac{y}{x} \tag{15}$$

where y is the time difference and x is the distance. Substituting the time difference and distance for air into equation 15 gave a value of $m = (2.02 \pm 0.01) \times 10^{-6}sm^{-1}$

The equation was then re-arranged into the form $y = mx$ and the distances were substituted into the equation to get corrections for the time difference. Since the laser travels through the 2 walls of the plastic box as well as the water itself the time difference due to the walls needed to be accounted for. This was done by subtracting the corrected time difference for the walls from the corrected time difference of the box filled with water. The results are shown in the table below.

Table 5: Time Differences Corrected Materials

Material	Distance (m)	Corrected Time difference (x10^{-6} s)
Air	0.520 ± 0.001	0 ± 0.01
Empty Box	0.520 ± 0.001	0.007 ± 0.01
Acrylic Rod	0.650 ± 0.001	0.22 ± 0.01
Box filled with water	0.501 ± 0.001	0.43± 0.02
Box filled with water	0.196 ± 0.001	0.35 ± 0.02

The refractive index was then calculated using this data and equation 8.

The refractive index of the acrylic rod was calculated to be $n_{rod} = 1.17 \pm 0.01$. The refractive index of water using the box filled with water and orientated lengthwise and width-ways was calculated to be $n_1 = 1.43 \pm 0.02$ and $n_1 = 1.92 \pm 0.05$. Averaging these two gave the refractive index of water to be $n_{water} = 1.68 \pm 0.04$

6 Conclusions

The speed of light in a vacumn from the direct and indirect method was found to be consistent with the published value to within three and one standard errors respectively. We were successful in measuring most parameters accurately with percentage errors of less than 1% however due to two of the data points varying significantly there was a large error in the gradient of 18%. Repeating measurements for each distance to get a mean time difference would help to eliminate these outliers.The main source of error in measuring the speed of light indirectly was from measuring the small lengths involved. The 20% error in rod separation and foil thickness can be reduced by measuring the separation and each foil thickness with vernier calipers. The large 32% error in the plate separation squared is hard to reduce without increasing the plate separation which requires use of a even higher voltage source we did not have access to.

The refractive index of the acrylic rod and water though precise, are not consistent with the published values to within three standard errors. They provide an order of magnitude estimate. The time difference could be measured more accurately by calibrating the signals and then placing the box of water or acrylic rod in place to see the time difference. This would remove the need to calculate corrections for the time difference and may give more accurate values for the refractive index.

7 Acknowledgements

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8 References

References

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9 Appendices

A Direct Method Data

LeyboldData.ods

B Functions Code

functions.py

C Direct Method Code

`speed_of_light.py`

D Magnetic Permeability Data

PermeabilityData.ods

E Magnetic Permeability Code

`magnetic_permeability.py`

F Electric Permitivitty Data

PermitivittyData.ods

G Electric Permitivitty Code

`electric_permitivitty.py`

H Refractive Index Data

DataMaterials.ods

I Refractive Index Code

`speed_of_light_medium.py`