# And Investigation into the Relationship of Distance between Slits and the Fringe Separation in a Double Slit Experiment

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# Finding the Relationship of Distance between Slits and the Fringe Separation in a Double Slit Experiment

## Introduction

A wave in physics is described as a propagation of disturbances from place to place in a regular and organized manner (Britannica), or simply the transfer of energy. Light is a type of electromagnetic wave. Thus like all waves, it is susceptible to diffraction and interference, as proven by Young's Double Slit experiment (Physics Libretexts).

By projecting monochromatic light through two small slits onto a surface, a pattern of bright fringes can be observed. The fringes occur as the two diffracted light sources from the fringes interfere with one another. By manipulating the distance between the two slits using different slits, the separation between observed fringes also changes. From the observed changes we can also find the wavelength of the light and compare it to the wavelength described on the laser used to determine accuracy.

## Background Information

Light is an electromagnetic wave, and it can be modelled as the movement of particles called photons. While in mechanical waves the transfer of energy occurs between oscillating particles such as those in water or air, electromagnetic waves consist of photons, which are massless particles whose energy consists entirely of motion (Hirvonen). As photons move in wave motion, they also exhibit the properties of waves. Diffraction occurs when a wave moves around an obstacle, causing the wave to spread out. Diffraction also occurs when a wave passes through an aperture with a similar or smaller width than the wavelength (NASA

Science). Using two slits, a monochromatic light source diffracts twice, producing the equivalent of two point sources of light. The two point sources are coherent with one another as they come from the same monochromatic source. Their interference creates a pattern of bright fringes.

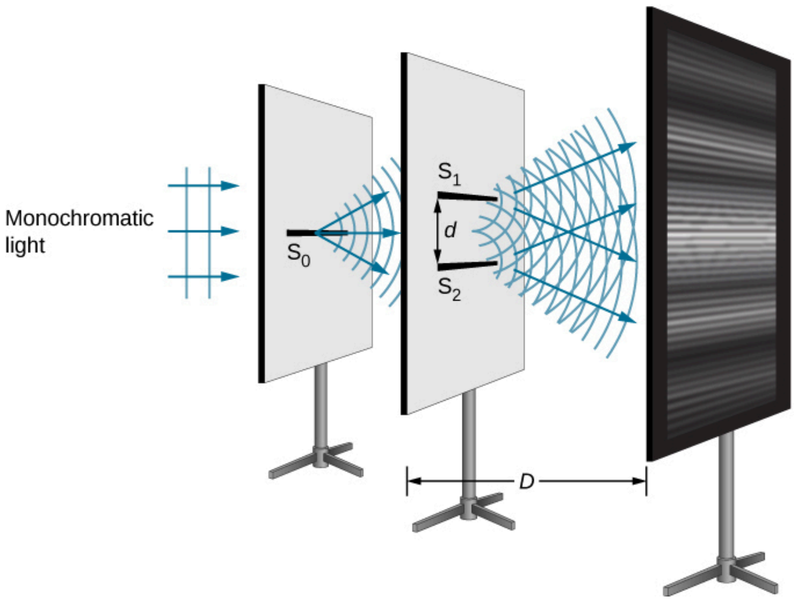

*Fig 1. A double interference set up (Physics Libretexts)*

The fringe pattern occurs as the wave superimposes on itself, where two waves combine to form a single wave where the displacement at each point is added together. When waves come crest to crest or trough to trough, amplitude is doubled through constructive interference and a bright maxima occurs on the screen. Where waves come crest to trough there is destructive interference, and amplitude is zero, resulting in a dark minima (Physics Libretexts). This phenomenon can be described by the following equation (Lumen Learning):

| $sin\theta d = \lambda m$ | |
| --- | --- |
| $\theta$ | Angle between the normal to the center of the slits and the fringe |
| $d$ | Distance between slits |
| $\lambda$ | Wavelength of the light passing through the slits |
| $m$ | Order of the fringe, starting from the center |

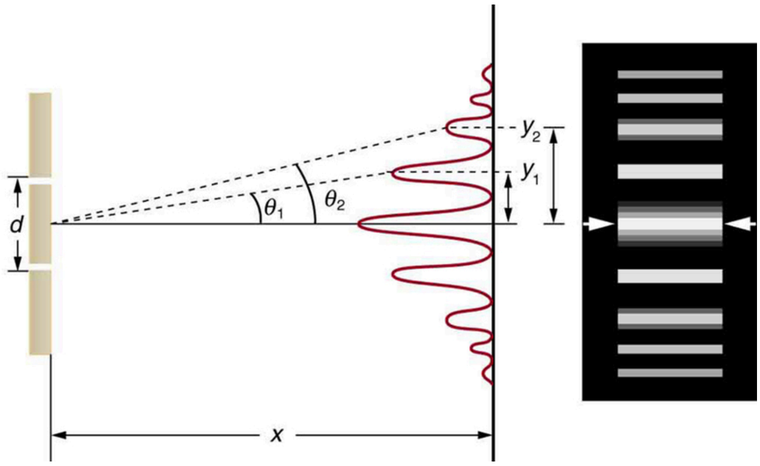

*Fig 2. Variables of the double slit equation (Lumen Learning)*

The spacing between subsequent fringes is equal (Roberts), and using trigonometry they can be related to the double slit equation.

| $tan\theta = y/D \approx sin\theta$ | |
|---|---|
| $y$ | Distance between the fringe and the first fringe, the fringe separation |
| $D$ | D = distance between the slits and the screen |

At small angles, sinθ is roughly equivalent to θ which is roughly equivalent to tanθ (Pierce). Thus $y/D$ can be assumed to be close to sinθ and substituted in the double slit equation: $\frac{yd}{D} = \lambda m$. By plotting $d = \frac{D\lambda m}{y}$ onto a graph, their relationship can be understood. As D and m are both constant variables, λ can be calculated to be compared with the value stated on the laser.

**Research Question**

*How does the distance between slits in a double slit experiment affect the separation between fringes projected onto a screen?*

## Hypothesis

As the derived equation for the relationship between the distance between slits and the separation between fringes is $d = \frac{D\lambda m}{y}$, the variables will likely have an inverse relationship. This is because the equation resembles $y = \frac{1}{x}$, where $distance\ between\ slits = y$ and $fringe\ separation = x$ which is the function for an inverse relationship.

## Variables

<u>Independent Variable</u>

The distance between slits, d, was the independent variable in this experiment. There were 5 different slits of incremental separation: 0.25mm, 0.30mm, 0.50mm, 0.75mm, 1.00mm. Ideally, distance between slits would increase in equal increments. However, there is an unequal interval between 0.25mm and 0.30mm due to the lack of other available slits.

<u>Dependent Variable</u>

The spacing between two subsequent fringes was the dependent variable of this experiment. It was manipulated by increasing the distance between slits, which should lead to a decrease in the fringe separation. As the distance between subsequent fringes is constant for any one slit width (College Physics), the separation between multiple subsequent fringes to constitute for multiple trials.

Controlled Variables

| **Variable** | **How it was controlled** | **Why it was controlled** |
|---|---|---|
| Wavelength of light, $\lambda$ | The same laser was used all throughout the experiment so that wavelength remained constant. | Wavelength is one of the variables in the used equation, so if it isn't controlled the relationship between d and y couldn't be found. |
| Distance between slits and screen | The same setup was used throughout the experiment, ensuring D remains constant. | Distance between slits and screen is used in the equation. If it isn't controlled the relationship between d and y couldn't be found. |
| Distance between slits and laser | The distance was kept at 200.0mm ± 0.5mm | The position of the laser was kept constant so that the intensity of the projected pattern remained the same. |
| Intensity of laser | The same laser was used all throughout the experiment | Ensures intensity is constant and all slits have the same apparent brightness. This makes measuring clearer. |
| Change in order of Fringe, $\Delta m$ | Only consecutive fringes were measured, so that the change in the order of fringes was $\Delta m = 1$. | $\Delta m$ is used in the equation, so if it isn't constant the relationship between d and y couldn't be found. |

## Apparatus

*Note: The uncertainty of the caliper and ruler is half of the smallest unit the device can measure (Luna, 1).*


*Fig 3. The labelling of the laser used in the experiment*

- 3B scientific double slit diaphragms with a width of 0.15mm and separations of 0.25mm, 0.50mm, 0.75mm and 1.00mm
- 3B scientific double slit diaphragm with a width of 0.15mm and a separation of 0.30mm
- Styrofoam stands to hold the laser.
- Wooden blocks for holding slits and screen
- Logitech Wireless presenter R400 Black with wavelength of 640-660nm.
- Caliper with uncertainty of ± 0.025mm
- 1 meter plastic ruler with uncertainty of ± 0.5mm
- Masking tape
- White cardboard
- Lenovo X1 Yoga Laptop
- Google Sheets Software (desktop)
- LoggerPro Software (desktop)

## Precautions

Lasers can cause damage if directly pointed at the eyes (Hazanchuk). For this reason the experiment was conducted in an isolated room and the laser was kept at a low height to prevent it hitting anyone's eyes. Masking tape was used to secure the setup into place. It was removed after the experiment was finished as there is a risk for the residue to damage surfaces when left for a long time (Nicks Building Blog).

### Experimental Assumptions

- All projected fringes are of equal width and are equally spaced for any one distance between slits.
- Light from the laser is fully coherent.

### Methodology

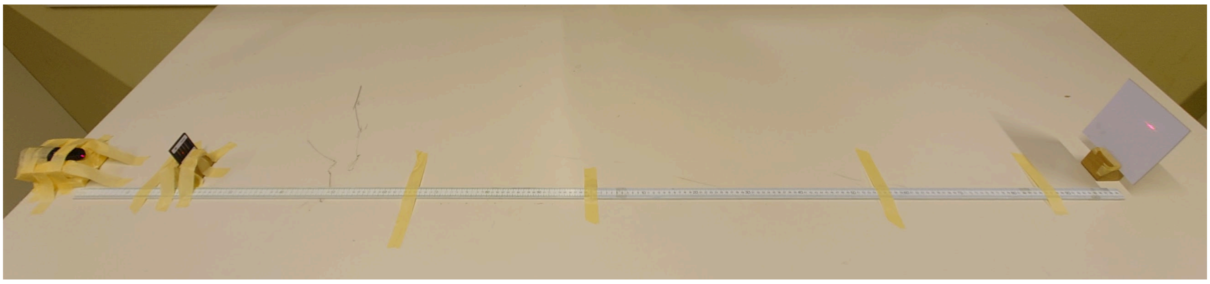

*Fig 4. A picture of the setup with the slit and the laser on the left side.*

1. Two 1-meter long rulers were placed end to end and taped to the table.
2. The cardboard screen is placed atop a wooden block with a slit in the middle, and taped into place so that the cardboard is aligned with the end of the ruler.
3. The laser is placed so that the frontmost point of the laser is aligned with the front of the ruler. A stand was carved out of styrofoam.. Masking tape is used to keep the laser and the stand in place.
4. The slit is placed 20 centimeters in front of the laser and fitted into a wooden block with a vertical slit. Tape is used to keep the stand still, but shouldn't touch the slit.
5. Remove all other sources of light from the room.
6. The laser is turned on and the slit is aligned to show an interference pattern on the cardboard.

7. A caliper is used to measure the width of the first 6 fringes, starting from the center fringe and continuing to the right.
8. A caliper is used to measure the distances between 1st-2nd, 2nd-3rd, 3rd-4th, 4th-5th and the 5th-6th fringes with the fringe width being included in the measurement. The brightest, center fringe is considered the 1st, and the rest are counted outwards from the 1st fringe. These measurements are the 5 trials for one distance between slits.

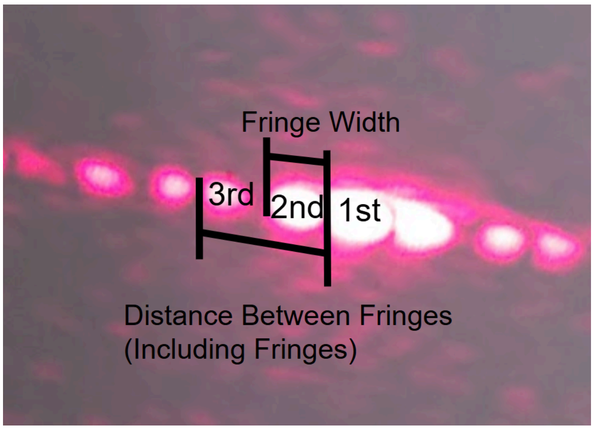


*Fig 5. A picture of the interference pattern with relevant measurements marked*

9. Record the values and change to a slit with greater distance in between and collect the measurements in step 8 for the new distance between slits.

### Preliminary Work

Several test trials were conducted in order to determine that the laser and the slits were functioning properly. These test trials also allowed me to determine the optimal lighting conditions for increased fringe visibility.

## Data Analysis

Raw Data Tables

| Separation (mm) | Distance between subsequent fringes, fringe included (mm) ±0.03mm | | | | |
|---|---|---|---|---|---|
| | 1st-2nd | 2nd-3rd | 3rd-4th | 4th-5th | 5th-6th |
| 0.25 | 8.30 | 8.35 | 8.00 | 8.45 | 8.20 |
| 0.30 | 6.90 | 7.00 | 6.95 | 6.80 | 7.00 |
| 0.50 | 4.60 | 4.65 | 4.45 | 4.75 | 4.55 |
| 0.75 | 3.25 | 3.25 | 3.30 | 3.35 | 3.20 |
| 1.00 | 2.20 | 2.20 | 2.05 | 2.25 | 2.15 |

The values are in 3 significant figures as that is what the caliper could measure. Processed data is also rounded to 3 significant figures for consistency.

| Separation (mm) | Width of fringe (mm) ±0.03mm | | | | | |
|---|---|---|---|---|---|---|
| | 1st | 2nd | 3rd | 4th | 5th | 6th |
| 0.25 | 3.40 | 3.40 | 3.30 | 3.20 | 3.35 | 3.45 |
| 0.30 | 2.85 | 2.80 | 2.95 | 2.80 | 2.70 | 2.90 |
| 0.50 | 2.35 | 2.25 | 2.25 | 2.05 | 2.20 | 2.15 |
| 0.75 | 1.45 | 1.60 | 1.55 | 1.60 | 1.55 | 1.55 |
| 1.00 | 1.00 | 1.15 | 0.95 | 1.05 | 1.10 | 1.00 |

Processed Data Tables

| Separation (mm) | Δy Distance between the centers of subsequent fringes (mm) u = ±0.06mm | | | | |
|---|---|---|---|---|---|
| | 1st-2nd | 2nd-3rd | 3rd-4th | 4th-5th | 5th-6th |
| 0.25 | 4.90 | 5.00 | 4.75 | 5.18 | 4.80 |
| 0.30 | 4.08 | 4.13 | 4.08 | 4.05 | 4.20 |
| 0.50 | 2.30 | 2.40 | 2.30 | 2.63 | 2.38 |
| 0.75 | 1.73 | 1.68 | 1.73 | 1.78 | 1.65 |
| 1.00 | 1.13 | 1.15 | 1.05 | 1.18 | 1.10 |

Each distance was calculated by subtracting half of the respective fringe widths from the distance between the fringes.

*Sample Calculation:* $4.90mm = 8.30mm - (\frac{3.40mm}{2} + \frac{3.40mm}{2})$

Uncertainty is calculated by summing together the uncertainties of the values used (Dinsmore, Hamilton College 2). As the width is divided by a constant number, the relative uncertainty stays the same while the absolute uncertainty is also divided by the constant (Dinsmore, Columbia University 9).

*Sample Calculation:* $u = 0.03mm + \frac{0.03mm}{2} + \frac{0.03mm}{2} = 0.06mm$

| Average and uncertainty (u) | | |
|---|---|---|
| Separation(mm) | Avg Δy (mm) | u (±mm) |
| | | |
| 0.25 | 4.93 | 0.21 |
| 0.30 | 4.11 | 0.08 |
| 0.50 | 2.40 | 0.16 |
| 0.75 | 1.71 | 0.06 |
| 1.00 | 1.12 | 0.06 |

The mean average of $\Delta y$ was calculated by summing all of the values for one separation, and dividing by the number of values summed (Indeed). The uncertainty was calculated as half of the range in the mean (Pearson, 3).

*Sample Calculations:*

$$Avg\ \Delta y\ =\ \frac{(4.90 + 5.00 + 4.75 + 5.18 + 4.80)}{5}\ =\ 4.93$$

$$u\ =\ \frac{(5.18 - 4.75)}{2}\ =\ 0.21$$

As $\Delta y$ is defined as the separation between the centers of two subsequent fringes, $1/\Delta y$ is the reciprocal of $\Delta y$. The values were obtained directly from the average for $\Delta y$. The percentage uncertainty of the mean $\Delta y$ was multiplied with $1/\Delta y$ to determine the absolute uncertainty.

| Average and uncertainty (u) | | |
|---|---|---|
| Separation(mm) | 1/Δy (mm⁻¹) | u (±mm⁻¹) |
| | | |
| 0.25 | 0.203 | 0.01 |
| 0.30 | 0.244 | 0.004 |
| 0.50 | 0.417 | 0.03 |
| 0.75 | 0.585 | 0.02 |
| 1.00 | 0.893 | 0.05 |

*Sample Calculations:*

$$Avg\ \Delta y\ =\frac{1}{4.93}\ =\ 0.203$$

$$u\ =\ \frac{0.21}{4.93} * 0.203\ =\ 0.01$$

| Average and uncertainty (u) | | |
|---|---|---|
| Separation(mm) | $\Delta y/\Delta m$(mm) | u (±mm) |
| | | |
| 0.25 | 4.93 | 0.21 |
| 0.30 | 4.11 | 0.08 |
| 0.50 | 2.40 | 0.16 |
| 0.75 | 1.71 | 0.06 |
| 1.00 | 1.12 | 0.06 |

Where $\Delta y$ is the fringe separation, $\Delta$m is the change in the slit order.As the measured slits were consecutive, $\Delta$m is always equal to 1. This means that for every value, $\Delta y/\Delta m = \Delta y/1 = \Delta y$ . As $m$ has no uncertainty, the uncertainty of $\Delta y/\Delta m$ remains the same.

*Sample Calculation:*

$\Delta y/\Delta m = 4.93/1 = 4.93$

Similarly, the reciprocal of the fringe separation divided by the change in number of the fringes is equal to the reciprocal of the fringe separation, hence: $\Delta m/\Delta y = 1/\Delta y$. As $m$ has no unit, the unit of $\Delta m/\Delta y$ is $mm^{-1}$.

| Average and uncertainty (u) | | |
|---|---|---|
| Separation(mm) | $\Delta m/\Delta y$ ($mm^{-1}$) | u (±$mm^{-1}$) |
| | | |
| 0.25 | 0.203 | 0.01 |
| 0.30 | 0.244 | 0.004 |
| 0.50 | 0.417 | 0.03 |
| 0.75 | 0.585 | 0.02 |
| 1.00 | 0.893 | 0.05 |

*Sample Calculation:* $\Delta m/\Delta y = \frac{1}{4.93} = 0.203 = \Delta y$

## Graphs

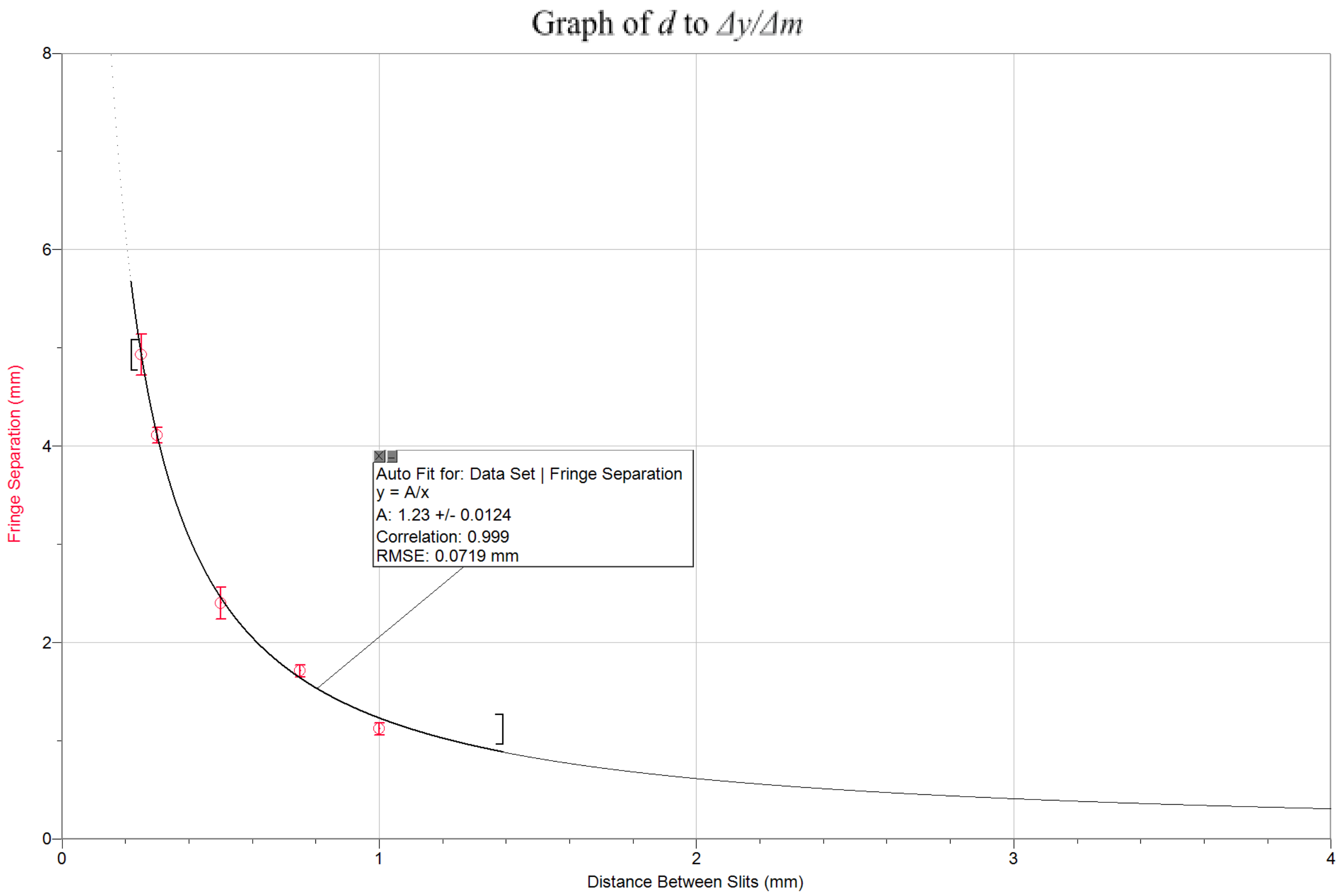


*Fig 6. The graph of d to Δy/Δm , adapted from LoggerPro*

The first graph put the dependent variable, $\Delta y/\Delta m$, into the y-axis, labelled the "Fringe Separation" and the independent variable, in the x-axis, labelled the "Distance Between Slits". The curve-fit tool in LoggerPro showed that an inverse function best fit the data points, with a very high correlation coefficient of 0.999.

This aligns with the derived formula, $d \ = \frac{D\lambda m}{y}$, where $y/m$ has an inverse relationship with $d$ . In both graphs, $y/m$ was used instead of just $y$, as $m$ also changes alongside $y$. This would mean that $d$ and $y$ don't have a proportional relationship. Meanwhile, $d$ and $y/m$ have an inverse relationship. Plotting in $d$ and the reciprocal of $\Delta y/\Delta m$, $\Delta m/\Delta y$, should yield a linear graph.

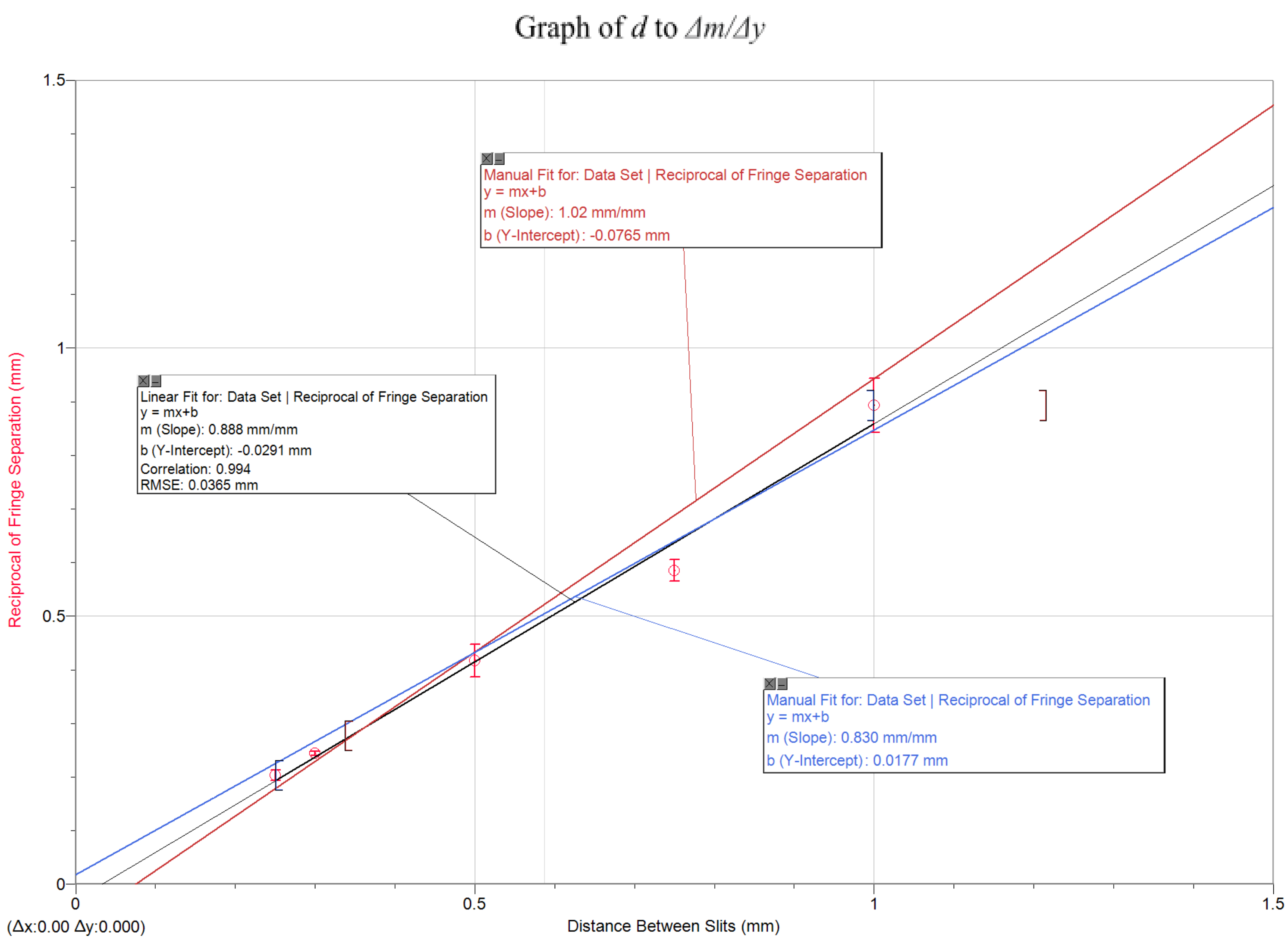


*Fig 7. The graph of d to Δm/Δy , adapted from LoggerPro*

The resulting graph has a gradient of 0.888, M, with a strong correlation coefficient of 0.994. The slope of the graph is 0.888, and there is a y-intercept of -0.0291, which might indicate a systematic error that has shifted all the data points downward. Normally the y-intercept should be zero as $\Delta m/\Delta y$ and $d$ are proportional.

The uncertainty in the gradient of the best-fit line can be determined using the minimum and maximum lines (Richmond). The maximum line goes from the lowest point of the first error bar to the highest point of the last error bar and has the greatest gradient. The minimum line goes from the highest point of the first error bar to the lowest point of the last error bar and has the smallest gradient. The uncertainty of the gradient equals half the difference between the gradients of the maximum and minimum lines (Richmond).

$u = \frac{1.02-0.830}{2} = 0.095 \approx 0.01$

The uncertainty is rounded to one figure (Luna) and as the last significant figure of a value should be in the same place as the uncertainty, the gradient is rounded as well.

$M = 0.888 \pm 0.095 \approx 0.89 \pm 0.01$

As the gradient can be defined as $M = \frac{\Delta y}{\Delta x}$ (Cuemath), the gradient in this case is $M = \frac{\Delta m/\Delta y}{d}$. This also means that the gradient has a unit of $mm^{-2}$, as $\Delta m/\Delta y$ has a unit of $mm^{-1}$ and is divided by $d$, which has a unit of mm. By substituting this value in the derived equation, we can get an estimate of the wavelength of the light, and compare it with the wavelength specified on the laser.

<u>Calculating Wavelength</u>

$\frac{\Delta m/\Delta y}{d} = \frac{1}{\lambda D} = 0.88mm^{-2} = \frac{1}{\lambda * 1800mm}$

$\frac{1}{\lambda} = 0.88mm^{-2} * 1800mm = 1584mm^{-1}$

$\lambda = \frac{1}{1584mm^{-1}} = 0.000631mm = 631nm$

<u>Calculating Uncertainty</u>

While the uncertainty of 1 ruler is $\pm\ 0.5mm$, a greater uncertainty will be considered for D, as multiple objects had to be aligned based on the ruler, each adding some uncertainty. As the two rulers had to be placed back to back, that adds $\pm\ 0.5mm$ uncertainty. Likewise, aligning the slits and the cardboard screen according to the ruler both add uncertainty.

$$u_t = 0.5mm + 0.5mm + 0.5mm = 1.5mm \approx 2mm$$

Therefore: $D = 1800mm \pm 2mm$

As there is no uncertainty specified on the distance between slits, the uncertainty can be assumed to be negligible in this case. The final fractional uncertainties can be calculated as:

$$u_M = \frac{0.01}{0.89} = 0.0112$$

$$u_D = \frac{2}{1800} = 0.00111$$

The final uncertainty is calculated by using the fractional or percentage uncertainty, which is summed when two values are multiplied or subtracted (Colombia University 8).

$$(0.0112 + 0.00111) * 0.000631mm = 0.000008mm = 8nm$$

Therefore the final value obtained for wavelength is:

$$\lambda = 631nm \pm 8nm$$

<u>Percentage Error</u>

The percentage error can be found by comparing the obtained value to the expected value (CalculatorSoup). The obtained value is very close to that specified on the laser itself, which was 640-660nm. They are given as absolute values.

$$Percentage\ error = \left|\frac{Experimental\ value\ - Theoretical\ value}{Theoretical\ value}\right| * 100\%$$

$$Percentage\ error\ (Lower) = \left|\frac{631nm - 640nm}{640nm}\right| * 100\% = 1.4\%$$

$$Percentage\ error\ (Greater) = \left|\frac{631nm - 660nm}{660nm}\right| * 100\% = 4.4\%$$

As the laser is imperfect, there is some uncertainty in the wavelength it produces. To account for this, the percentage error for both the lower and greater wavelengths stated on the laser was taken. For the lower wavelength of 640nm, the obtained value is only 1.4% smaller. For the greater value, the obtained wavelength is 4.4% smaller. Overall this is quite a small percentage error.

$$Percentage\ error\ (Avg)\ =\ \left|\frac{631nm - 650nm}{650nm}\right| * 100\%\ =\ 2.9\%$$

For this case, the average of the two wavelengths provided on the laser were compared with the obtained value. The average expected value is 650nm and has an uncertainty of $\pm\ 10nm$, which means the greatest it can vary between 660nm and 640nm as stated on the laser. The obtained value is 2.9% smaller than the expected average. While this is quite a small percentage error, the obtained value is not within the range of the expected value, as it only ranges from 623nm to 639nm, meaning that there must have been some errors affecting the measurements.

## Conclusion

### Relationship Between Independent and Dependent Variables

The data table for the average $\frac{1}{\Delta y}$ shows that as the distance between slits increases, the fringe separation decreases. This answers the research question by showing that distance between slits and fringe separation have an inverse relationship to one another. Likewise, the reciprocal of the fringe separation increases proportionally to the distance between slits. This conclusion also supports my hypothesis, which compared the equation $d\ =\frac{D\lambda m}{y}$ to $y\ =\frac{1}{x}$.

The graphs also support this conclusion. The first graph which directly maps d to y, shows a hyperbola, indicating an inverse relationship

The second graph showed that the inverse of y/m, m/y, was directly proportional to d as when graphed they produced a straight line. Linear relationships can be defined as y=x, where y is directly proportional to x.

$\frac{m}{y} \propto d$

**Sources of Error**

Systematic Error

In graph 2, which shows the linear relationship between m/y and d, there is a non-zero y-intercept. The y intercept is -0.0291 when it should be zero. This is because m/y and d are proportional, as can be seen in the final formula:

| | |
|---|---|
| $\frac{m}{y} = 0$ | $d = 0$ |
| $d = \frac{D\lambda m}{y} = D\lambda * 0 = 0$ | $d = \frac{D\lambda m}{y} = 0$ |

A systematic error could have reduced accuracy by shifting all the measurements downwards (Exell). Ideally, the systematic error shouldn't have an effect on the obtained results if all values were shifted down equally, as the value was obtained through using the gradient, which wouldn't change. If the systematic error shifted some values down more than others, it could change the gradient of the graph, resulting in a different result.

Percentage Error

Even with the possibility of a systematic error causing some inaccuracy, the percentage error is still small; less than 5% when looking at the greatest possible error. Based on the average wavelength provided by the laser, it is about 3%.

Random Error

Uncertainty is small, with the final result having a percentage uncertainty of only 1.1%. This indicates that random error likely didn't have a significant impact on the calculated value.

**Comparison to Other Studies**

Trends

The nature of the relationship can be compared to other sources, which state that slit separation and the spacing of fringes have an inverse relationship (UBC Mathematics, Tutorchase), similar to the conclusions of this experiment.

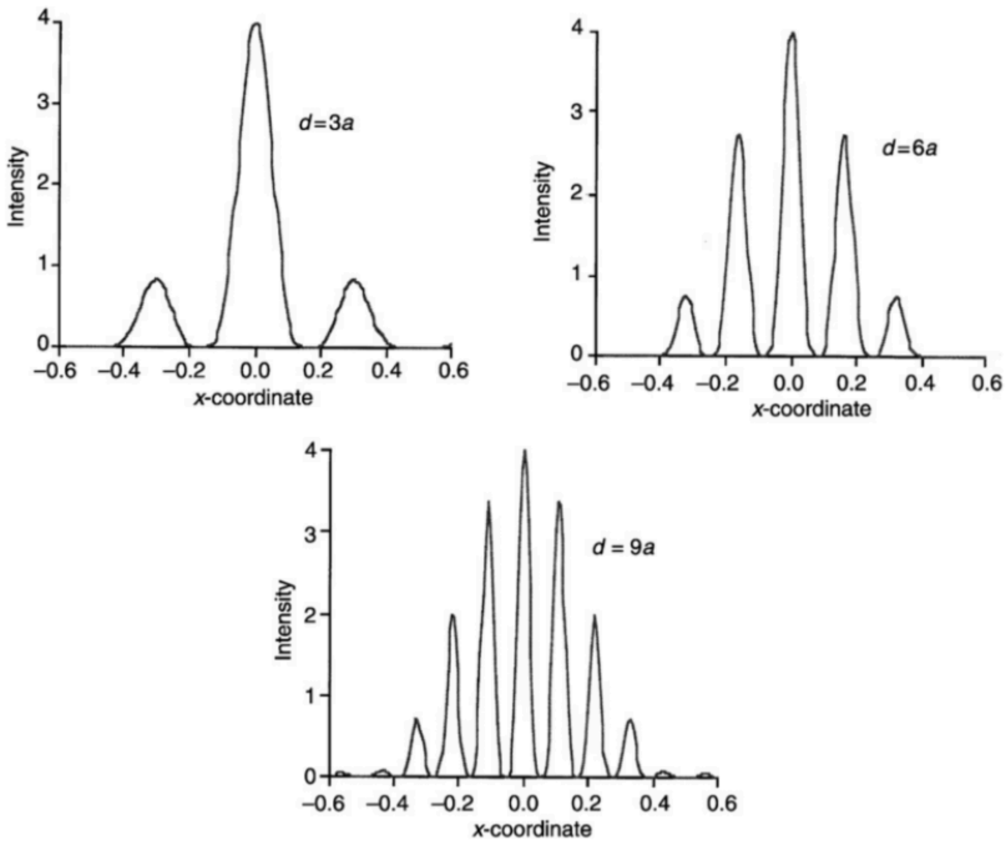

*Fig. 8 Graphs showing how the slit separation, d, affects the distance between fringes(Guenther, 75).*

The graphs in Figure 7 show how as the slit separation d, increases from 3a, to 6a and 9a, the distance between fringes decreases (Guenther, 75). As the y-axis is intensity, the fringes can be identified as the spikes in intensity that decrease as they move outward from the x-coordinate 0.0. Thus as the distance between slits increases, the fringe width and spacing decreases (International School Bangkok).

Methodology

Measuring the slits was a manual process, likely resulting in increased random error. Other experiments instead use light sensors (Neumann, 3) or CCD cameras (Hylkelma, 21) to map out the interference patterns, which could reduce random error.

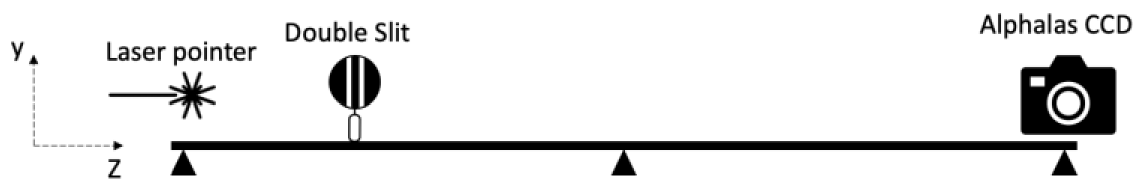


*Fig. 9 An diagram of a double slit experiment using a CCD camera (Hylkelma, 21)*

Most experiments use a rail setup, where the slit, laser and screen are all mounted onto a rail. This ensures that the distance between the slits and the screen and the distance between the laser and slits remains constant, both of which are controlled variables.

# Evaluation

## Limitations and Improvements

The use of a caliper likely caused some parallax error (Mini Physics). The parallax error occurs due to the caliper being placed above the surface it is measuring. When viewed at an angle, the measurement appears slightly shifted than what it actually is. As I measured the slits from the right side, the fringes might have been measured as smaller separation than they actually were. As wavelength was calculated as $\lambda = \frac{d\Delta y}{D}$, if the fringe separation, $\Delta y$ , is measured as smaller than in reality, it could be the reason the wavelength was calculated to be less than the value stated on the laser.

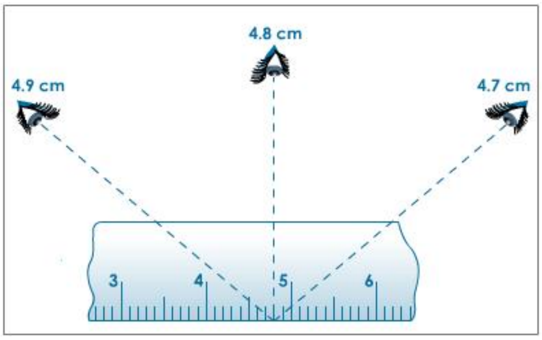

Fig 10. An example of parallax error on a micrometer screw gauge (Miniphysics)

Measuring the width of the fringes digitally through pictures of the setup for each slit or using graphs created by a light sensor with a translation stage (Neumann) would eliminate the parallax error.

Poorly-defined fringes could have led to some inaccuracy, as it was difficult to determine where the fringes exactly ended and started. This is due to the fact that lasers inherently vary somewhat in wavelength (Photonics). Ideally a laser for professional applications, with less variation in wavelength would be used, which would reduce the random error.

Lastly, ambient lighting likely interfered with the light from the laser (Baraz). The room was darkened to reduce this interference as much as possible. This interference caused the interference patterns to be less clearly defined, leading to increased random error. A completely dark environment for the experiment would solve this issue.

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