International Baccalaureate
PHYSICS HL

EXTENDED ESSAY

The effect of varying the slit width on a diffraction system with a glass slab placed in front and examining the change in the angle of first minima by utilizing single slit intensity graph

Word Count: 3108

May 2025

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1. Introduction

During my studies in the DP, I have come across various topics in physics and saw their extent. However, the topic of waves stood out from the rest as it considered all types of waves and especially light. Exploring and researching about how light behaviour is in general is a well-known physics topic. Behaviour of light was said to be in a dual nature as it was proved in both ways that it acted as a wave or a particle. Diffraction of light by slits prove and help us quantify its properties by utilizing the wave phenomena. It therefore paves the way for further scientific research like optical microscopes, spectrometers and laser technology. One thing that drew my attention about light was that in what manner can we interfere or change properties of it. As a glass user myself, knowing the refraction and re-direction of light to the eye, led me to researching about how mediums affect the light rays and so the refractive index. I found out that the most suitable material that I was able to obtain on the market was a glass slab of uniform thickness. I was interested in how this glass material with different refractive index would affect the intensity distribution in terms of first minima measurement on the viewing screen. I also wanted to utilize the small angle approximation understanding to and so, I decided to perform this as the experiment topic for my extended essay. Understanding how different refractive indices affect light could uncover new methods production of optical devices or materials. The equipment used in this exploration is the Vernier Diffraction Apparatus. It is an adequate equipment to conduct this experiment as it allows a detailed observation of intensity pattern of laser light. Furthermore, calculations were made during the process of measurement to convert the measured data to the desired value which was radians.

2. Background Information

2.1 Diffraction and Related Experiments

Diffraction is the action of waves spreading out in all forward directions after passing through a slit. When a wave passes through the slit, the slit acts as if it is a light source on its own as waves enter and spread into regions created by the slit. (Jewett & Serway, 2008) These region creations are referred to interference patterns where waves encounter one another, creating constructive or destructive interferences, further creating what is called a diffraction pattern on a viewing screen with a central maximum (Halliday et al., 2007) As seen in ***Figure 1.*** This is a result of Huygens's Principle which explains how the spreading of wavefronts interferes with themselves and create a secondary source of waves called wavelets, shown in ***Figure 2.***

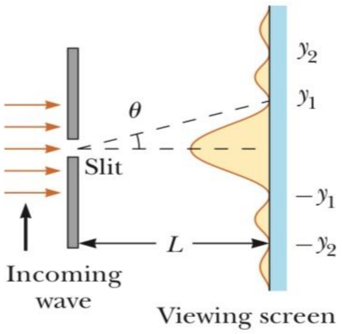


Figure 1. Fraunhofer Diffraction Pattern of single slit (Jewett & Serway, 2008)

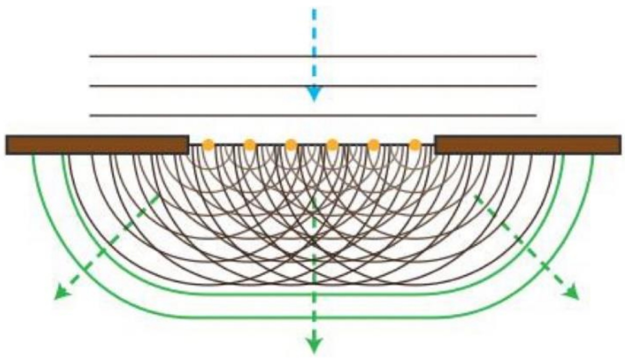


Figure 2. Huygens's Principle with wavelets (Tsokos, 2014)

The single-slit diffraction pattern includes intensities of light seen on viewing screen known as intensity pattern. The main properties of single slit intensity pattern include fringe widths and the distribution of intensity values. The intensity differentiation between fringes across the viewing screen can be seen on ***Figure 1.*** with a central maximum intensity at the middle. As stated above, each portion of the slit acts as a source of light wave according to the Huygens's

Principle and so an interference between multiple sources occur. The resultant light intensity therefore would depend on the direction angle of the rays. Moreover, an explanation can be made according to the figure below:

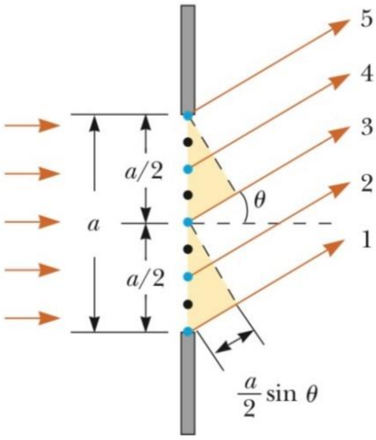


Figure 3. Paths of light rays passing through a narrow slit and diffract towards a direction (Jewett & Serway, 2008)

When the rays 1 and 3 are considered, ray 1 travels faster than ray 3 by a value equal to the path difference for halved wavefront shown with *(a/2) sin θ* in which "a" is the width of the slit. Correspondingly, this path difference between rays is also applicable for 2 and 4, 3 and 5 and so on. So, it is proven that a ray from centre travels less than the one at the bottom edge of the slit and arrives out of phase compared to the others and causes destructive interference (Halliday et al., 2007) As seen in *Figure 3.* The path difference could also be stated as *a sin θ* if we don't divide the slit width by 2 and a destructive minimum can be seen when this phase difference is an exact multiple of wavelength giving us the equation for destructive minimum as:

$$a\ sin\theta = m\lambda$$

And for constructive maximums:

$$asin\theta = (m + \frac{1}{2})\lambda$$

Where;

a: Slit width (mm)

θ: Angle of direction of the light from central maxima (rad)

m: Order of minimum

λ: Wavelength (λ)

Destructive minimums form dark fringes on the viewing screen on a single slit diffraction system and constructive forms the patterns of light. It is important to note that the derivation of these formulas is made according to the first minimum so m = 0. This gives us the equation;

$$path\ difference = \frac{\lambda}{2} = \frac{a}{2} sin\theta$$

In this case, we identify $sin\theta \approx \theta$ because of the angle itself being very small, we assume it if it doesn’t make any change in its value if we take it as a sine or not. This gives us a general equation for the determination of minimums as;

$$\theta = \frac{\lambda}{a}$$

Furthermore, from *Figure 1.*it can be seen that;

$$tan\theta = \frac{y1}{L}$$

Where;

y_1: The distance from the middle part of the central fringe to the minimum

L: The distance between the slits and the viewing screen

Using the small angle approximation described above, $sin\theta \approx tan\theta \approx \theta$. According to this information, the whole equation of destructive minimum also identified above could be written as;

$$y1 = \frac{m\lambda L}{a}$$

When Figure 1. is reconsidered again, it can be seen that at the central maximum, the central part where the light arrives, the greatest fringe width exists among other fringes. This is named **The Central Maximum Fringe Width**, which is double the value of y since it spans over y1 andy1, giving us a general 2y. Therefore, we multiply the y value by 2 to find the total width.

$$Central\ Fringe\ Width = \frac{\lambda L}{a} \times 2$$

When a glass plate of a specific thickness is placed in front of the slit, the properties of glass, in this case, the refractive index, would affect the light passing through. The speed of light changes because the medium directly affects the wavelength of light. The wavelength of light passing through the specific medium with a different refractive index than in air experiences a shortened wavelength, experiencing a decrease in propagation speed (Gallegos & Stokkermans., 2023). This could be written as;

$$v = \frac{c}{n}$$

Where:

c: speed of light in vacuum

n: refractive index of glass

The relation of frequency with speed of light and wavelength is given by;

$$f = \frac{c}{\lambda}$$

The speed of light changes because the medium directly affects the wavelength of light. The wavelength of light passing through the specific medium with a different refractive index than in air experiences a shortened wavelength, experiencing a decrease in propagation speed (Gallegos & Stokkermans, 2023).

A notation could be created on how wavelength changes in different media as:

$$\lambda_{medium} = \frac{\lambda}{n}$$

We now can further apply this lambda derivation for minimum determination. It was previously determined that a formula for central bright fringe and minima was present. However, another approach to them can be created using trigonometric properties to relate the angle-based minima formula to central maximum. The diagram below shows a modified version of *Figure 1*.

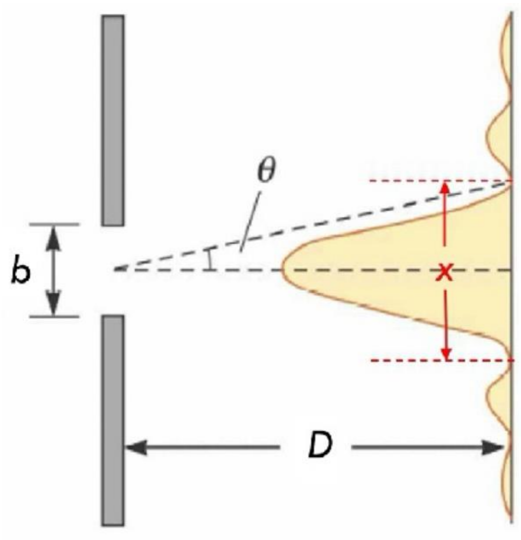


Figure 6. Display of Intensity Distribution graph

The width of central maximum can be found as follows:

$$\theta \approx tan\theta = \frac{x/2}{D}$$

$$x = 2D\theta$$

Now, λ_{medium} can be written in the form:

$$\theta = \frac{\lambda_{medium}}{a} \rightarrow \theta_{medium} = \frac{\lambda}{an}$$

The parameter “m” wasn’t written because it is first minimum which would correspond to 1.

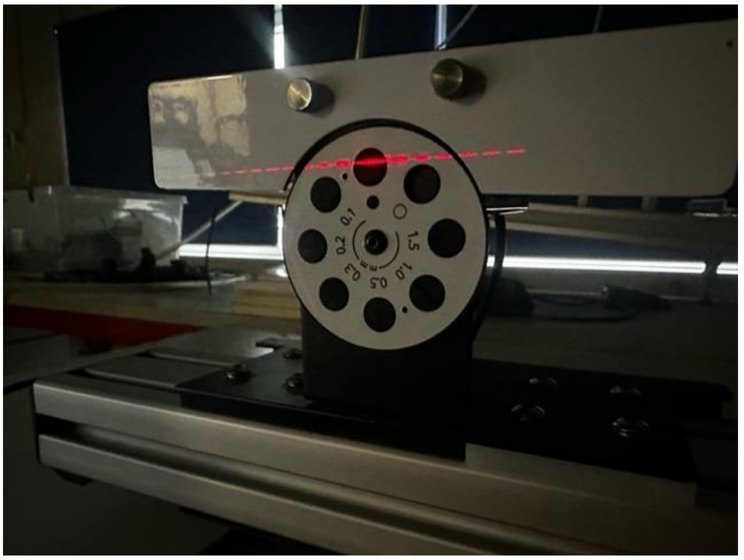


Figure 7. Diffraction Pattern Formed with 0.04mm wide slit without glass

3. Prior Experimentation Information

3.1 Research Question and Aim

How does the slit width in a diffraction experiment affect the shift in the position of first minima caused by the glass block placed in front of the slit?

The aim of this experiment is to determine in what terms are the properties of light are affected by changing light source width with a glass of a specific thickness present in front of the source on a single slit diffraction-based setup.

3.2 Hypothesis

- The position of first minima will decrease with a glass of thickness 1.5cm present, decrease and will also become narrower with increasing slit widths (0.02, 0.04, 0.06 0.08, 0.10, 0.12, 0.14 and 0.16mm)

- **Explanation:** The reason for this hypothesis comes from the previously derivated notation of *position of first minimum* where it could be determined that as “a” increase, the shift should decrease and, as slit width increases, the diffraction effects decrease.

3.3 Variables:

- **Independent Variable:** Slit widths (0.02, 0.04, 0.06 0.08, 0.10, 0.12, 0.14 0.16mm) used in the diffraction, determined by the manufacturer’s information.

Dependent Variable: The shift in the angular position of the first minima when a glass block of refractive index 1.7 is placed between the slits and the viewing screen. This will be measured by using a Vernier High Sensitivity Light Sensor combined with a Linear Positioning Sensor through the LabQuest 2 Interface with 5 trials conducted for each slit width. First minima Shift will be measured in millimetres (mm) and further going to be converted into radians.

Controlled Variables:

Table 1. Controlled Variables

Controlled Variables	Why it was controlled	Method of control
Refractive Index of glass slab	Since I was experimenting on how light behaves in specific media and attempting to simulate devices, I had to make sure that a glass of specific thickness -a known medium- was present in front	I obtained a glass slab and cut it to specific dimensions length 10cm, width 5cm and a thickness of 1.5cm. According to the manufacturer, the refractive index was 1.7.

	of my light source. This was a necessary variable to know and control. If this wasn’t controlled, the theoretical calculations would’ve been wrong and so the uncertainty calculations.	
Distance between the slit and the light sensor	This was a factor that would affect the fringe width since the fringe width formula derivated in the background information includes a “D” variable the maintained at a constant distance of 100.0 ± 0.2 cm.	The components attached on the rail of the setup weren't moved when repeating trials in the experiment.
Background light intensity in the Lab Environment	Any external sources of light would've had the potential to affect my values, and this maintenance ensured that no other source affected the light patterns formed.	All the trials were conducted in a darkened lab environment.
Wavelength of laser light	The same monochromatic red laser of wavelength 635 ±5 nm was used as varying colours would have different	The same Vernier Red Diffraction Laser of wavelength 635 ± 5 nm was

	wavelengths which would directly affect the results obtained.	used throughout the experiment.
Speed of Linear Positioning Sensor and Light Sensor while measurement process	If the speed of the sensor varied, the pattern formed would not be reliable since some points couldn't have been properly identified by the light sensor.	The testing trials had absurd patterns of intensity, and I concluded that moving the sensor through at a relative constant speed ensured a smoother, more readable graph

3.4 Materials:

Table 2. Materials	
Vernier Linear Positioning Sensor combined with High Sensitivity Light Sensor	Glass slab of dimensions 5cm, 10cm, 1.5cm
Vernier Diffraction Single Slits of widths 0.02, 0.04, 0.08 and 0.16mm	LabQuest 2
Vernier Red Diffraction Laser (635 ± 5 nm)	Computer

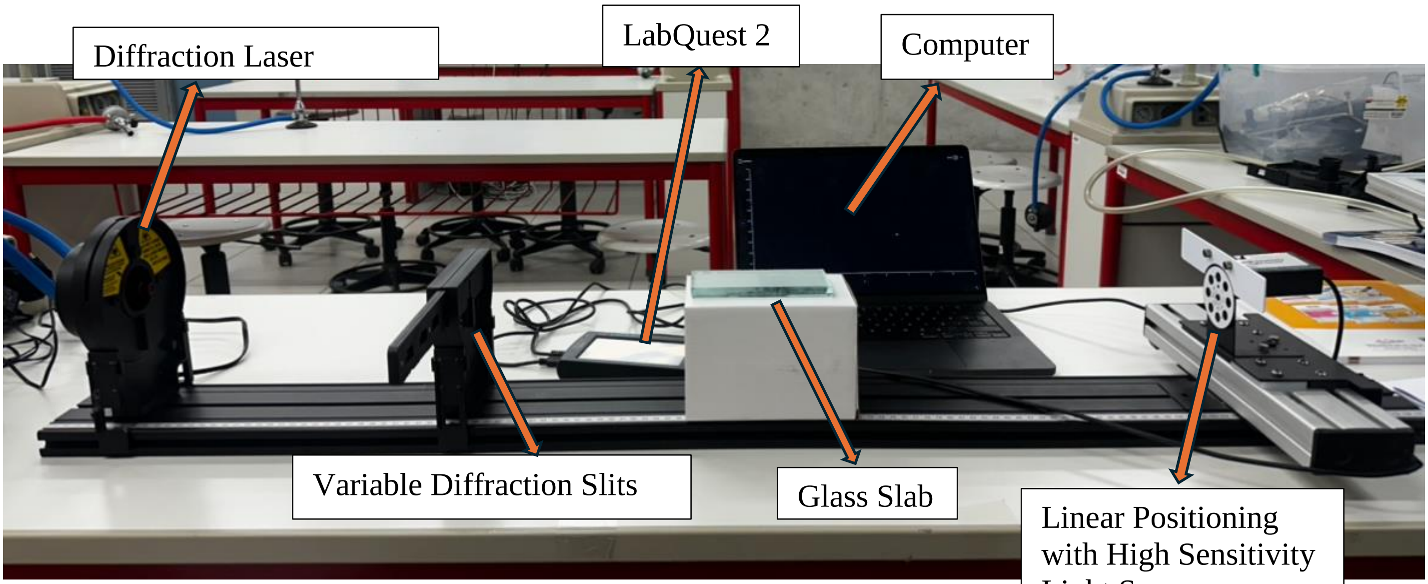


Figure 8. Experiment Setup

3.5 Methodology

Apparatus Preparation

1. Set the optics rail on a table and position the diffraction laser, aligning it with the 0cm mark as seen on *Figure 8.*
2. Position the slits in front of the laser, approximately 30cm away from it and set the slits to single slit setting.
3. Position the Linear positioning and the high sensitivity light sensor 71.5cm away from the slits.
4. Open Vernier Graphical Analysis App on computer and connect the sensor components to LabQuest 2 Interface and then the interface to the computer which transfers the graph/ data to the app.
5. Calibrate both sensors on the computer to zero.
6. Place the glass slab horizontally in front of the slits.

Conducting Trials

1. Open the laser and align it with the slit by ensuring light doesn't get blocked by it.
2. Switch the slit to 0.02mm
3. Slide the sensor combination towards right and switch its aperture to 0mm to get visible graphs
4. Start the measurement by pressing start button on the interface and gradually slide the sensor from right to left at a relatively constant speed, avoiding fast and very slow moves.
5. Save the intensity-position graph on LabQuest and transfer it to the computer.
6. Repeat steps 1-5 for other slit widths as well

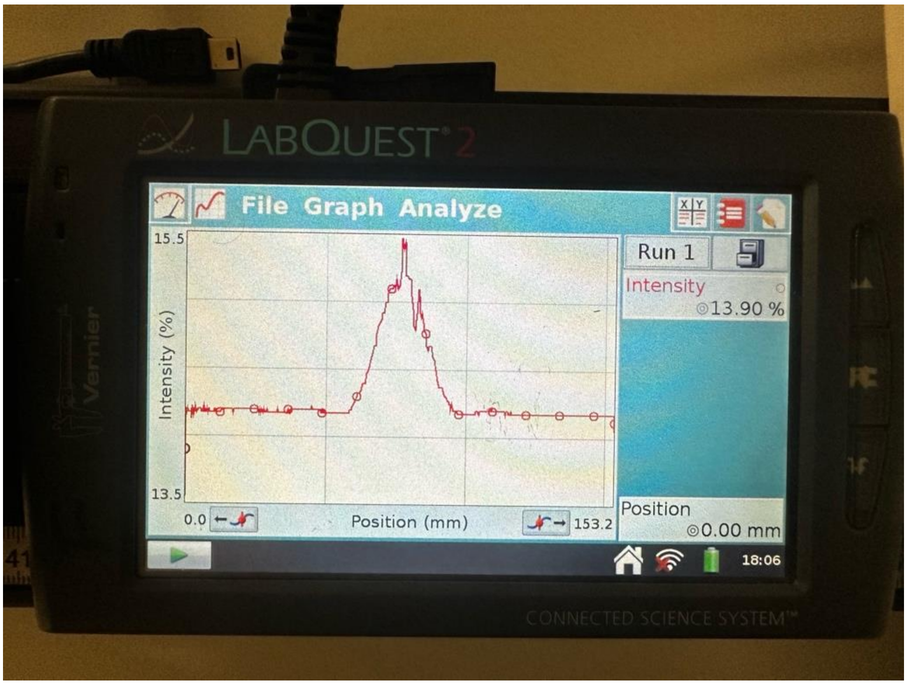


Figure 9. An Improper graph created that represents not maintaining a constant speed with linear positioning sensor during measurement

4. Analysis

4.1. Analysis of Data:

Data was collected over a span of day and estimated to be 5 hours.

4.2 Quantitative Data

4.2.1: Raw Data:

	Graph Readings of First minima without glass introduced (mm)				
Slit Width	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**
0.02	31.70	31.54	31.63	31.61	31.82
0.04	16.09	15.98	16.01	16.05	16.07
0.06	10.55	10.57	10.53	10.54	10.59
0.08	7.90	7.96	7.88	7.93	7.91
0.10	6.32	6.36	6.33	6.37	6.30
0.12	5.32	5.27	5.26	5.30	5.31
0.14	4.50	4.52	4.48	4.54	4.49
0.16	4.01	3.95	3.98	4.02	4.00

Table 3. Represents the linear position of first minima recorded in millimetres without glass

	Graph Readings of First minimum with glass introduced (mm)				
Slit Width	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**
0.02	18.66	18.60	18.68	18.59	18.62
0.04	9.31	9.33	9.30	9.33	9.35
0.06	6.20	6.25	6.23	6.18	6.26
0.08	4.63	4.68	4.65	4.62	4.68
0.10	3.76	3.72	3.77	3.75	3.70
0.12	3.09	3.13	3.15	3.10	3.12
0.14	2.70	2.63	2.60	2.68	2.64
0.16	2.34	2.32	2.29	2.33	2.31

Table 4. Represents the linear position of first minima recorded in millimetres with glass

The raw data tables show the separation of first minima to the central maximum in the setup with and without glass placed between the slits and the viewing screen. A further conversion to radians is done in the following calculations section.

1) **Mean Value Calculations:**

Mean value calculations were made for both with and without glass trials

$$\boldsymbol{average = \frac{sum\ of\ trial\ values}{number\ of\ trials}}$$

$$average\ first\ minimum\ position = \frac{31.70 + 31.54 + 31.63 + 31.61 + 31.82}{5}$$

$$= \mathbf{0.032\ m}$$

$$average\ first\ minimum\ position = \frac{18.64 + 18.60 + 18.65 + 18.59 + 18.62}{5}$$

$$= \mathbf{0.01862\ m}$$

2) **Theoretical Calculations:**

Theoretical approach to the calculation of first minima with specific slit width without glass and with glass respectively is as follows.

$$\theta = \frac{\lambda}{an}$$

$$\Delta x = \frac{L\lambda}{a} = L \times \theta$$

Therefore,

$$\theta = \frac{\Delta x}{L}$$

Furthermore, converting the experimental values to radians,

$$0.03166\ rad\ , 0.01862\ rad$$

Also calculating the theoretical values,

$$first\ minimum, 0.02mm\ slit = \frac{635 \times 10^{-9}}{0.02 \times 10^{-3}} = \mathbf{0.03175}\ \boldsymbol{rad}$$

$$first\ minimum, 0.02mm\ slit = \frac{635 \times 10^{-9}}{1.7 \times (0.02 \times 10^{-3})} = \mathbf{0.01867}\ \boldsymbol{rad}$$

Therefore, the change in position of first minimum was calculated by subtracting air trial from glass trial.

$$0.03166 - 0.01862 = \mathbf{0.01304}\ \boldsymbol{rad}$$

3) <u>Absolute Uncertainty Calculations:</u>

$$with\ glass = \frac{0.03182 - 0.03154}{2} = \pm\ \mathbf{0.00014}\ \boldsymbol{rad}$$

$$without\ glass = \frac{0.01868 - 0.01859}{2} = \pm\ \mathbf{0.00005}\ \boldsymbol{rad}$$

$$0.00014 + 0.000045 = \pm\mathbf{0.000185}\ \boldsymbol{rad}$$

4) <u>Percentage Uncertainty Calculations:</u>

$$\%\boldsymbol{error} = \left(\frac{\boldsymbol{experimental\ value - theoretical\ value}}{\boldsymbol{theoretical\ value}}\right) \times \mathbf{100}$$

Theoretical values were calculated before and therefore a table was constructed,

$$\left(\frac{0.03166 - 0.03170}{0.03170}\right) \times 100 \approx \mathbf{0.13}\ \%$$

The data calculated in theoretical calculations are presented below with the experimental data.

Measurements in Air (rad)	
Theoretical	Experimental
0.03170	0.03166
0.01580	0.01604
0.01050	0.01056
0.00790	0.00792
0.00635	0.00634
0.00529	0.00529
0.00453	0.00451
0.00390	0.00399

Measurements in glass (rad)	
Theoretical	Experimental
0.01860	0.01863
0.00930	0.00932
0.00622	0.00622
0.00470	0.00465
0.00373	0.00374
0.00311	0.00312
0.00266	0.00265
0.00230	0.00232

Tables 5. and 6 Angle of first minima processed with and without glass

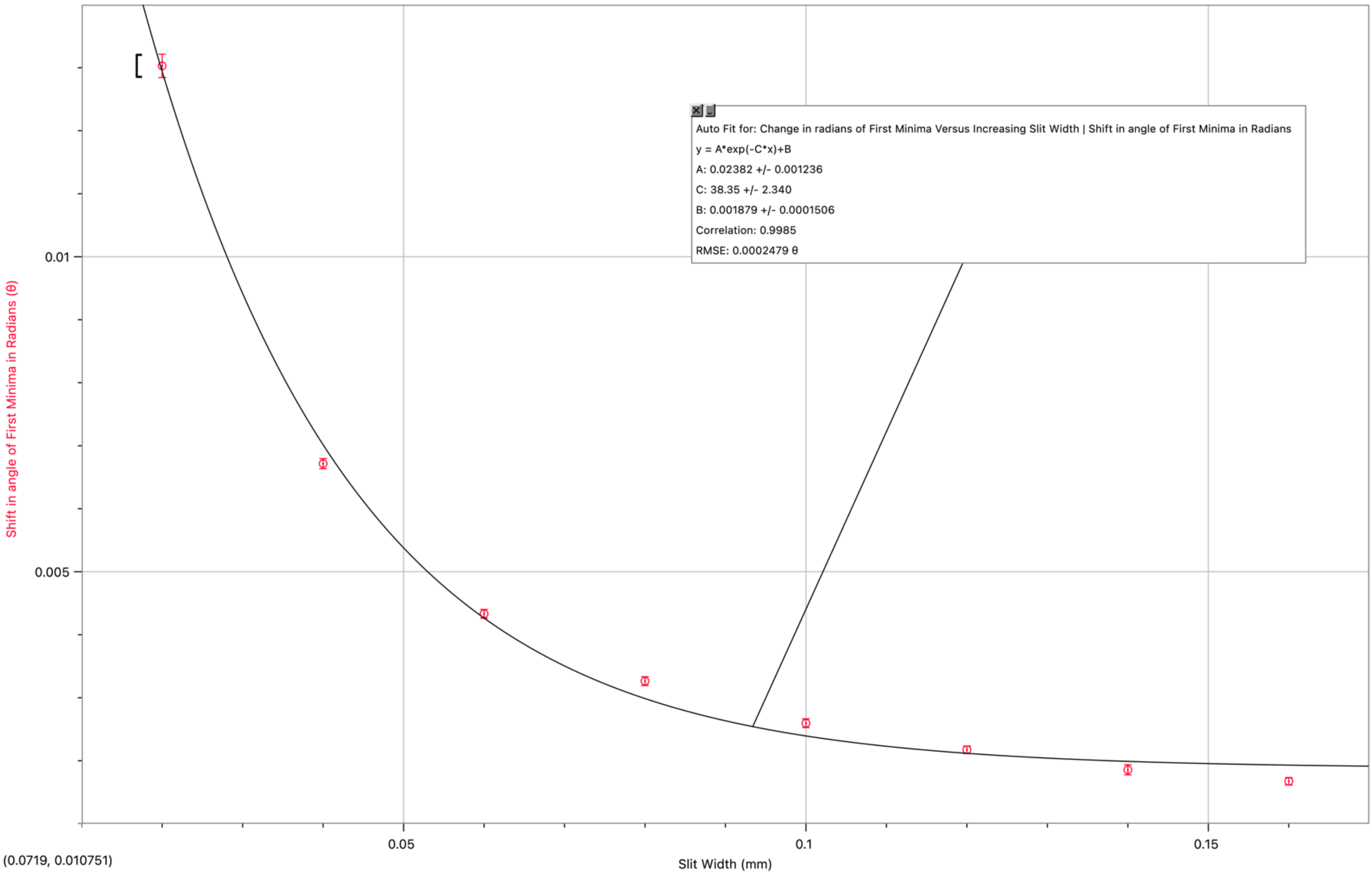
These values are listed to present the percentage uncertainty calculations and to follow up the upcoming processed data table. The theoretical values are calculated using the $\theta = \frac{\lambda}{na}$ formula on the *theoretical calculations* section.

4.2.2 Processed Data:

Slit Width (mm)	Refractive Index (n)	Average Angle of First Minima (radians)	Change in the angle of First Minima (radians)	Absolute Uncertainty (radians)	Percentage Uncertainty
0.02	1	0.03166	0.013030	0.000185	%0.13
	1.7	0.01863			%0.16
0.04	1	0.01604	0.006716	0.000080	%1.52
	1.7	0.00932			%0.26
0.06	1	0.01056	0.004332	0.000070	%0.53
	1.7	0.00622			%0.06
0.08	1	0.00792	0.003264	0.000070	%0.20
	1.7	0.00465			%1.02
0.10	1	0.00634	0.002596	0.000070	%0.22
	1.7	0.00374			%0.27
0.12	1	0.00529	0.002174	0.000060	%0.26
	1.7	0.00312			%0.04
0.14	1	0.00451	0.001856	0.000080	%0.53
	1.7	0.00265			%0.38
0.16	1	0.00399	0.001674	0.000060	%2.36
	1.7	0.00232			%0.78

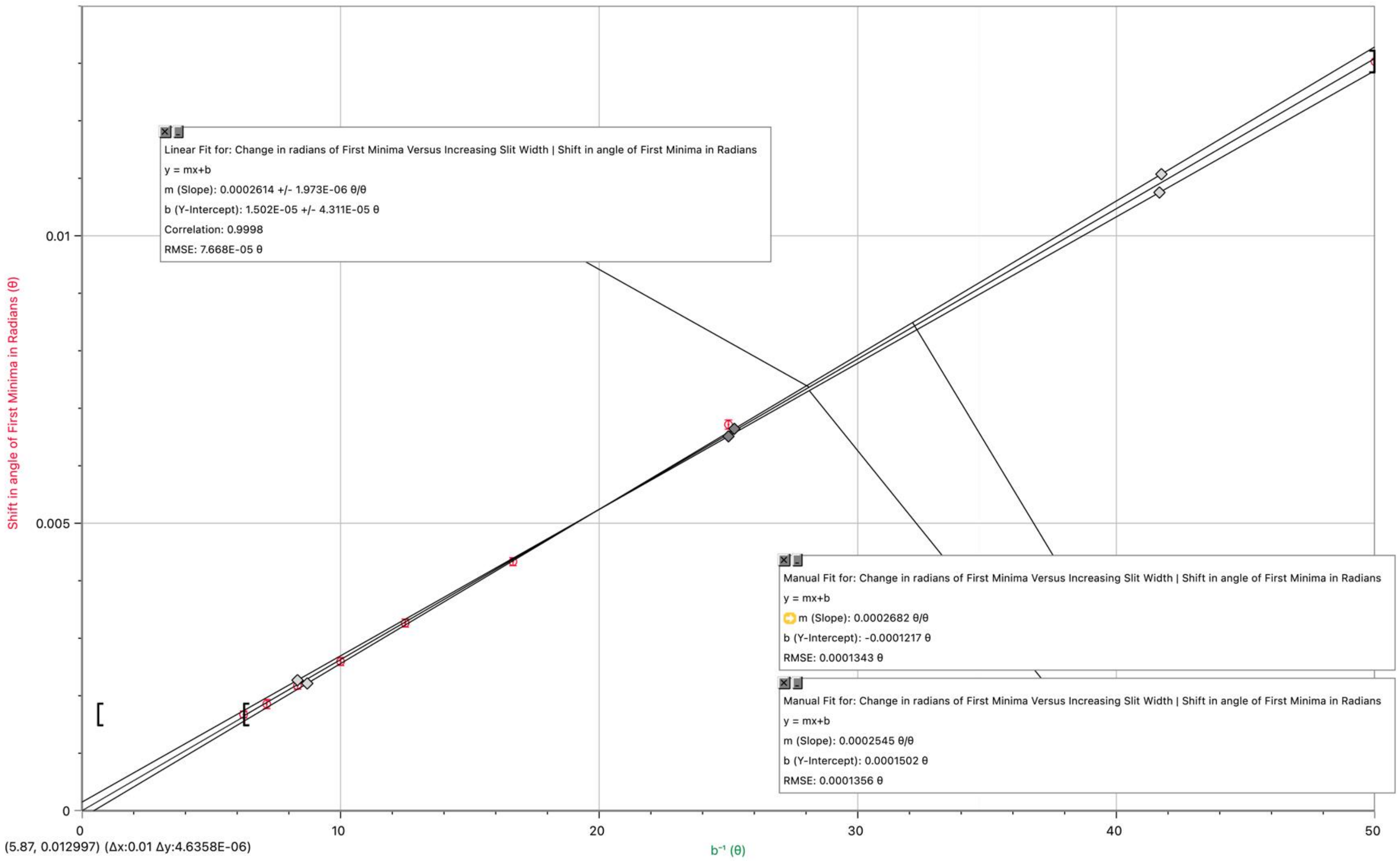
Table 7. Uncertainties and average values of radian data obtained

The slit widths uncertainty wasn’t included because they were determined by the manufacturer and so it didn’t have an uncertainty.



Graph 1. The change in the first minimums' radians with slit widths with their absolute uncertainties

The graph above shows an exponential data set with plotted uncertainties. It shows that the varying slit width and shift in angle are inversely proportional to each other. Furthermore, a gradient interpretation graph could be seen below.



Graph 2. The change in the angular position of first minima depending on slit width in a diffraction pattern with gradient uncertainty and max/ min gradient lines plotted

The graph above was created by taking $\frac{1}{b}$ values of data plotted on the x-axis and so it was linearized. Hence, an uncertainty value of $\pm\, \mathbf{1.973 \times 10^{-6}}$ in the best-fit line was determined. The maximum and minimum gradient lines were plotted to represent worst lines. Furthermore, a series of experimental error calculations were made according to the information from the graph. An experimental error calculation was therefore made from the gradients of maximum and minimum lines;

$$\left(\frac{Gradient_{max} - Gradient_{min}}{2}\right) \times 100$$

$$\left(\frac{0.0002682 - 0.0002545}{2}\right) \times 100 \approx \mathbf{6.4 \times 10^{-4}}\%$$

5. Conclusion

This experiment aimed to analyse and quantify the effect of varying slit widths (0.02, 0.04, 0.08, 0.10, 0.12, 0.14 and 0.16mm) with an introduction of a glass with thickness 1.5cm to the single slit diffraction system. The introduced glass had a refractive index of 1.7 and it was placed in front of the source. The experiment mainly focused on the changes in the first minima position and its geometrical interpretation. Therefore, necessary equations utilizing the small angle approximation were created and calculations were made considering the position accordingly. The calculations and measurements were made based on the graphical representations from the Vernier Diffraction Apparatus. The hypothesis commented that the first minima position measurement with a glass block will decrease as refractive index introduced combined with increasing slit widths would result in a narrower and shortened position of first minimum, creating an inversely proportional understanding. This relationship could also be proven from the best-fit line of the *Graph 1.*

Considering *Graph 1*, It could be said that as the slit width increases, the change in radians of first minima decreases and looking at *Table 7.*, It is interpreted that the average angles with and without glass on the system also decrease, proving a relation between the table and the graph created. Hence, *Graph 1.* displays an exponential best fit line which proved the inverse proportionality between changing slit width and change in the angular position of first minima. The R^2 value of the graph had a value of 0.9985 which signifies a relatively strong correlation with a best fit line gradient $\mathbf{0.0002614 \mp 1.973 \times 10^{-6}}$, maximum line gradient **0.0002682** and minimum line gradient **0.0002545**. Furthermore, the equation and the correlation coefficients obtained signify great relation and interpretation when the scale of the experiment is considered. The hypothesis, made from the theoretical formula created, proved to be true and was accepted. Hence, the obtained values were satisfactory.

The scientific community literature regarding this type of experiment was limited and no direct approach to such an experiment and evidence in the literature. Although I couldn't access any relevant experiments close to the one made, I managed to depend on the background information section of this study where theoretical formulas and knowledge were proved and determined. These aspects supported the reliability of this study's results. Also, considering the percentage errors and that the fact that the data were small scaled, no values exceeded 10% which is considered acceptable (Hafiz, 2023). The suggested reason for percentage errors varying between values is that because the experiment setup had significantly precise details like attempting to align the laser source with the slits every time after a trial, moving the sensors at a constant speed and re-calibrating the sensors. These factors were constantly tried to maintain however, no specific, precise adjusting was made and minimal variations in these factors might have caused these percentage errors while obtaining data.

6. Evaluation

6.1 Strengths:

Strength	Explanation
Low percentage errors	Considering the experiment was small scale, the obtained percentage errors of radians of first minima were acceptable being below 10% and necessary explanations for their presences in the experiments were made and were sensible.
High Number of trials	Having high number of trials ensured that the measurements were being conducted appropriately and that each data obtained were related to each other. This also contributed to the absolute uncertainties.
Acceptable Absolute Uncertainties	Absolute uncertainties obtained from the first minima values were relatively low, making a great representation of the graph further created.
Diffraction pattern created	Even though it was necessary to re-calibrate sensors and re-position the laser every time after each trial, the diffraction pattern created was reliable and theoretically satisfactory
Time of the experiment	All sections of the experiment were done over the course of the same day, ensuring the conditions of the lab environment

Table 8. Strengths and their explanations in the experiment

6.2 Weaknesses and Limitations

Error	Effect on Results	Improvements
Absence of literature values related to the experiment	The final interpretations of the experiment were made according to the theoretical approaches and determinations which may not be sufficient entirely for the experiment	The research question may have been shaped to relate to one of the studies made before on the literature in order to test the accuracy of results
The properties of the glass used	The glass used throughout the experiment was cut out and the sides were not perfectly smooth. Also, it had scratches throughout the surface and inside which might have caused very small unwanted deflections and polarization	A more properly designed polycarbonate glass, especially for lab and optics experiment use could have been preferred instead of cutting one.

Table 9. Errors and their effects on the experiment with potential improvements

6.3 Extensions

The experiments area of consideration could be increased to include different colors of lasers which would create more significant results to consider and easily interpretable ones. Also, a longer glass could've been preferred as the path of the light would have increased and allow for more specific observations. The extensions would potentially increase the scope and enhance the interpretation abilities of the experiment.

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