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Interference and Diffraction of Light

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Abstract

This experiment measured diffraction and interference patterns from single and double slits using a scanning light sensor. Slit widths and separations were obtained through feature analysis and curve fitting, and the results agreed with the expected values. The structure of the double slit pattern matched the single slit diffraction envelope, including the number of visible interference maxima. Measurements with different slit widths also supported the uncertainty relation. Overall the data show clear consistency between the observed patterns and the theoretical descriptions of diffraction and interference.

Contents

1	Introduction	1
2	Materials and Methods	2
3	Data and Analysis	3
3.1	Single Slit	3
3.2	Double Slit	4
3.3	Quantum Mechanical Interpretation	6
3.4	Questions	7
4	Conclusion	8
5	References	9
6	Appendix	10
6.1	Appendix A: Python Code for Double Slit Analysis	10
6.2	Appendix B: Python Code for Feature-Based Slit Measurement	11
6.3	Error Propagation in the Slit Width a	12
6.4	Error Propagation in the Slit Spacing d	12
6.5	Error Propagation for the Uncertainty Principle	13

1 Introduction

Light passing through narrow openings produces patterns that reveal its wave nature. In this experiment the intensity of laser light is measured across diffraction and interference patterns in order to study how geometry of the slit affects the angular position of maxima and minima. By comparing single slit diffraction with double slit interference, the characteristic features of each pattern can be identified and used to determine physical quantities such as slit width and slit separation.

For a single slit of width a , the angles of the minima satisfy

$$a \sin \theta = m' \lambda, \quad (1)$$

where θ is the angle measured from the center of the pattern, λ is the wavelength of the laser, and m' is the order of the minimum.

For a double slit of separation d , the angles of the bright maxima satisfy

$$d \sin \theta = m \lambda, \quad (2)$$

where m counts the maxima starting from the central bright region.

The diffraction intensity envelope for a single slit is described by

$$I(\phi) = I(0) \left(\frac{\sin \phi}{\phi} \right)^2, \quad \phi = \frac{\pi a}{\lambda} \sin \theta, \quad (3)$$

where $I(0)$ is the central intensity and ϕ represents the phase parameter associated with the aperture size.

The diffraction intensity for a double slit is described by

$$I(\theta) = I_0 \left(\frac{\sin \alpha}{\alpha} \right)^2 \cos^2 \beta, \quad \alpha = \frac{\pi a}{\lambda} \sin \theta, \quad \beta = \frac{\pi d}{\lambda} \sin \theta. \quad (4)$$

Where d is the distance between the center of the two slits.

The experiment also allows a connection with quantum concepts. A photon passing through a slit of width a has position uncertainty $\Delta y = a$. The first diffraction minimum gives the angular spread of the outgoing light, which provides an estimate for the momentum uncertainty Δp_y . Using the relation

$$\Delta p_y = \frac{h}{a}, \quad (5)$$

and combining with Δy , we obtain a statement consistent with the Heisenberg uncertainty relation,

$$\Delta y \Delta p_y \approx h. \quad (6)$$

Finally combining Equation 5 and 6 gives

$$\frac{a}{\lambda} \sin \left(\tan^{-1} \left(\frac{l}{b} \right) \right) = 1 \quad (7)$$

which this experiment will attempt to verify.

The goal of this work is to record diffraction and interference patterns, extract peak and minimum positions, determine slit parameters, and examine how these observations relate to the theoretical framework above[1].

2 Materials and Methods

The experiment was performed on a rigid optics rail that held the laser source, slit disk, and scanning light sensor in a fixed arrangement. A red laser diode provided a narrow beam that passed through selected apertures on a slit disk mounted in a lens holder. The disk contained several single and double slits with known widths and separations, and it could be rotated to place the desired slit in the path of the beam. A light sensor was mounted on a movable scanner arm driven by a low speed motor. The arm contained an encoder that recorded the sensor position along a travel distance of fourteen centimeters while the sensor measured light intensity.

The main equipment included the red laser diode, the slit disk with single and double slit apertures, the scanner arm with encoder, the linear translator rail, and the computer interface. The computer program titled *Interference and Diffraction* was used to monitor the scan, to adjust gain on the sensor, to place measurement cursors on the intensity graph, and to export the numerical data.

To align the instrument the scanner arm was moved to the central region of its track. The laser beam was directed through the slit and onto the sensor aperture by adjusting the vertical and horizontal controls of the laser mount. The slit disk was placed a few centimeters from the laser and rotated until the correct slit was centered on the beam. After alignment the sensor was moved back so the beam did not strike the detector during setup. The gain on the detector was set to a reasonable value, usually ten, and room light was minimized to avoid unwanted background intensity.

For each slit configuration the sensor was moved to one side of the pattern and a full scan was initiated through the software. The motor carried the light sensor across the diffraction or interference pattern while the program recorded intensity and position. The scan stopped when the arm reached the end switch. The positions of maxima and minima were measured using the on screen cursors, and these values were used to determine slit width and slit separation from the theoretical relations. The numerical data were also exported as a text file for further analysis in Python[1].

After testing different gain settings on the light sensor and different slits on the mask on the front of the light sensor; it is determined that 100x gain produce the cleanest data, and slit #6 work best for single slits, whereas slit #4 work best for double slits.

Throughout the experiment, the distance between the light sensor and slit wheel is $L = 1.064 \pm 0.0005$ m, and the wavelength of the laser is $\lambda = (650 \pm 10) \times 10^{-9}$ m.

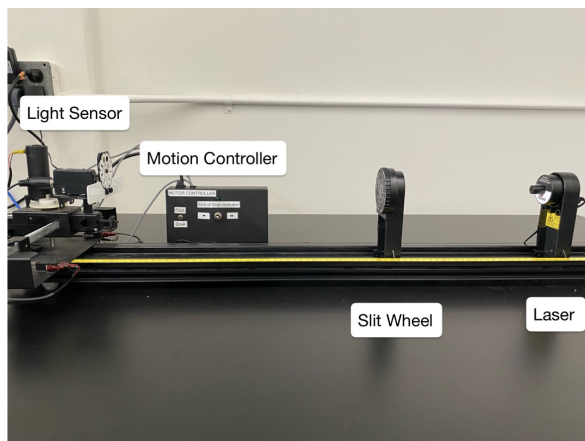


Figure 1: Schematic of the laser, slit disk, and scanning light sensor used to measure diffraction and interference patterns.[1]

3 Data and Analysis

3.1 Single Slit

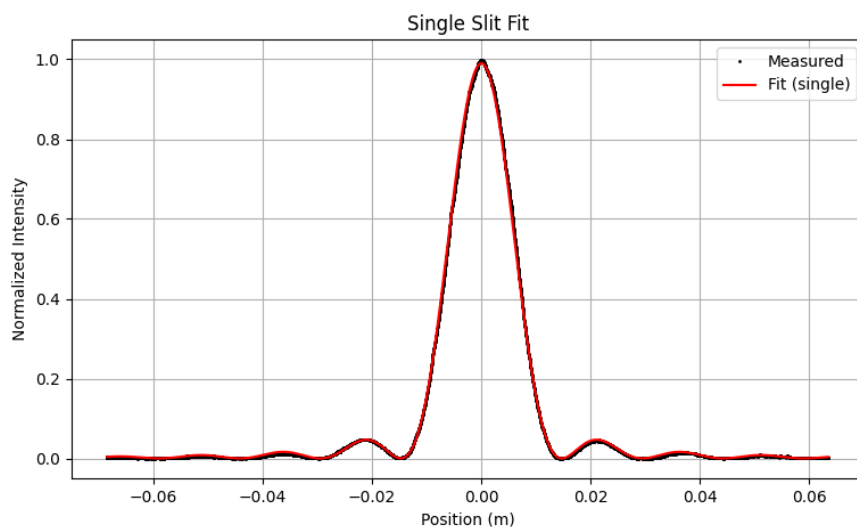


Figure 2: Measured and Fitted Intensity vs Position For Single Slit, $a = 0.04\text{mm}$

For method 1, manual reading, 2 minima are read from both sides of the center maxima from Figure 2. Their positions relative to the center maxima are:

$$\Delta x = 0.01475, 0.02954, -0.01473, -0.02946 \text{ m}$$

Their respective a values are calculated using Equation 1. Taking a simple arithmetic average yields slit width $a = 0.0469 \pm 0.00072 \text{ mm}$ (see Appendix 5.2 for error propagation). For method 2, fitting the smoothed Intensity vs Position graph to Equation 3 produced the exact same slit width, as shown again in Figure 2.

3.2 Double Slit

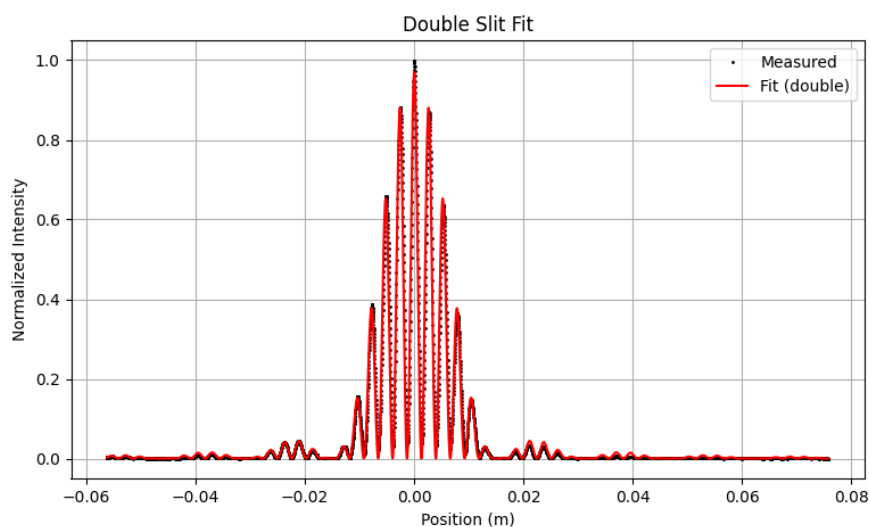


Figure 3: Measured and Fitted Intensity vs Position For Double Slit, $a = 0.04\text{mm}$, $d = 0.25\text{mm}$

Using method 1, manual reading, 2 maxima are read from both sides of the center maxima from Figure 3. Their positions relative to the center maxima are:

$$\Delta x = 0.00260, 0.00522, -0.00262, -0.00523 \text{ m}$$

Their respective d values are calculated using Equation 2. Taking a simple arithmetic average yields slit separation $d = 0.266 \pm 0.004 \text{ mm}$ (see Appendix 5.3 for error propagation).

The first diffraction minima is $\Delta x = 0.01452 \text{ m}$. The calculated value of slit width using Equation 1 is $a = 0.0476 \pm 0.0007 \text{ mm}$.

Using method 2 to fit the data to Equation 4, as shown in Figure 3, produced: $a = 0.0448 \text{ mm}$, $d = 0.2622 \text{ mm}$. Which agrees with the values produced by method 1.

The experimentally obtained value for slit separation $d = 0.266\text{mm}$ agrees with the value listed on the slit disc of 0.25mm . However, the obtained value for slit width is larger than the suggested value. This discrepancy is consistent through multiple trails, suggesting that $a = 0.04 \text{ mm}$ is likely the correct value for slit width.

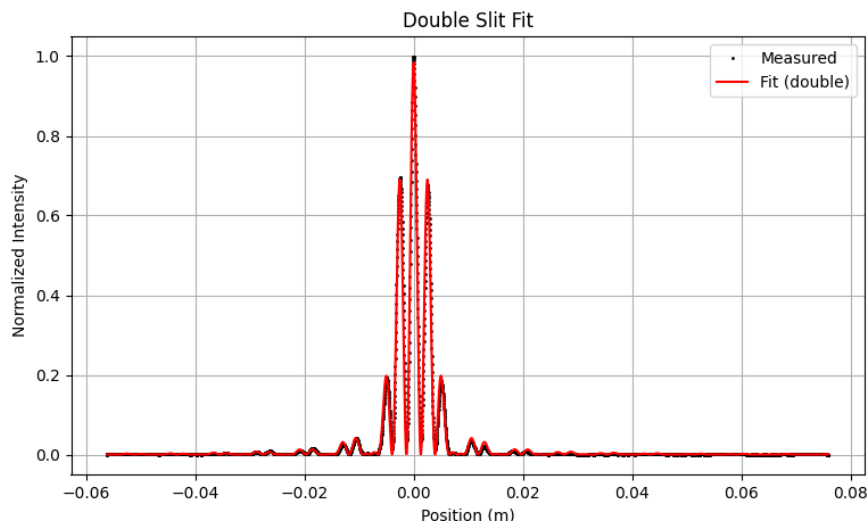


Figure 4: Measured and Fitted Intensity vs Position For Double Slit, $a = 0.08\text{mm}$, $d = 0.25\text{mm}$

Repeating the experiment for $a = 0.08\text{ mm}$, $d = 0.25\text{ mm}$. Using two interference maxima on either side of the center maxima and using Equation 2 obtained $d = 0.2627 \pm 0.005\text{ mm}$. Using the first diffraction minima on one side of center maxima and Equation 1 gives $a = 0.0871 \pm 0.0007\text{ mm}$. Fitting the data to Equation 4, as shown in Figure 4, yields similar values with $a = 0.0867\text{ mm}$, $d = 0.2636\text{ mm}$. Again the slit separation agrees with suggested, while slit width is larger.

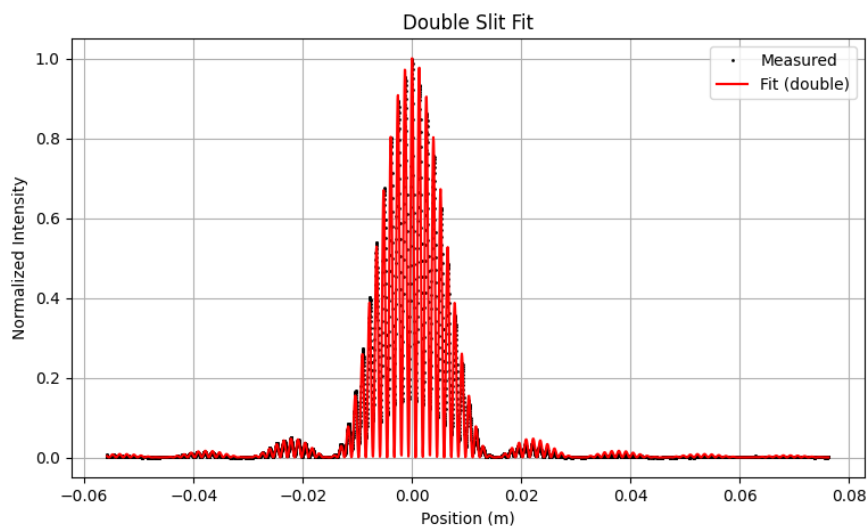


Figure 5: Measured and Fitted Intensity vs Position For Double Slit, $a = 0.04\text{mm}$, $d = 0.50\text{mm}$

Repeating the experiment one more time for $a = 0.04\text{ mm}$, $d = 0.50\text{ mm}$. Using two interference maxima on either side of the center maxima and using Equation 2 obtained $d = 0.528 \pm 0.008\text{ mm}$. Using the first diffraction minima on one side of center maxima and Equation 1 gives $a = 0.0456 \pm 0.0007\text{ mm}$. Fitting the data to Equation 4, as shown

in Figure 5, yields similar values with $a = 0.0452$ mm, $d = 0.5304$ mm. Again the slit separation agrees with suggested, while slit width is larger.

3.3 Quantum Mechanical Interpretation

We will verify Equation 7 with 3 different single slit widths, $a = 0.02$ mm, 0.04 mm, 0.08 mm as shown on the slit disc.

For $a = 0.04$ mm, it is already determined in section 3.1 that the actual slit width is $a = 0.0469 \pm 0.00072$ mm. The half width of the center maximum is $l = 0.01475$ m. The left side of Equation 7 with these values is 0.999 ± 0.021 (see appendix 5.4 for error propagation). This is consistent with the Heisenberg uncertainty principle.

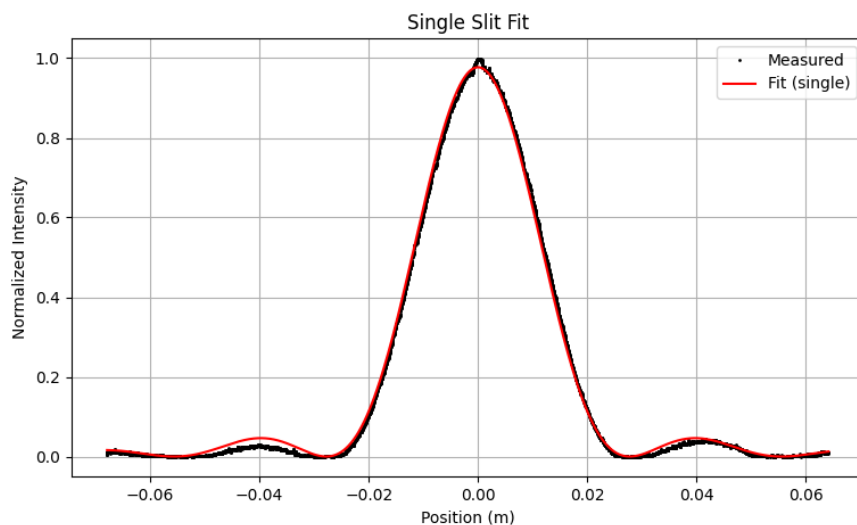


Figure 6: Measured and Fitted Intensity vs Position For Single Slit, $a = 0.02$ mm

For $a = 0.02$ mm, same methods in section 3.1 are used again to find actual slit width $a = 0.02486 \pm 0.00038$ mm, with the fitted graph shown in Figure 6. The half width of the center maximum is $l = 0.027816$ m. The left side of Equation 7 with these values is 1.000 ± 0.022 . This is again consistent with the Heisenberg uncertainty principle.

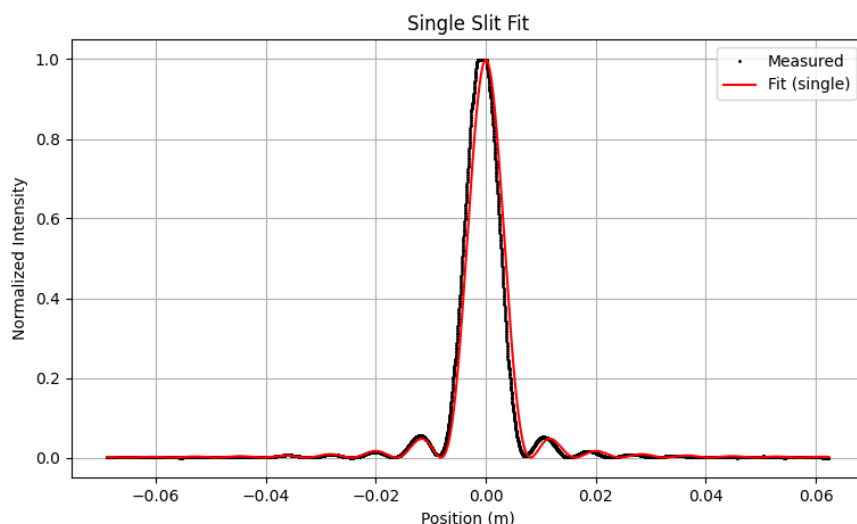


Figure 7: Measured and Fitted Intensity vs Position For Single Slit, $a = 0.08\text{mm}$

For $a = 0.08\text{ mm}$, same methods in section 3.1 are used again to find actual slit width $a = 0.0848 \pm 0.0013\text{ mm}$, with the fitted graph shown in Figure 7. The half width of the center maximum is $l = 0.008149\text{ m}$. The left side of Equation 7 with these values is 0.999 ± 0.022 . This is one more time consistent with the Heisenberg uncertainty principle.

3.4 Questions

1. What physical quantity is the same for the single slit and the double slit?

The angular position of the diffraction minima is determined solely by the slit width a . Thus, the *single-slit diffraction envelope* is the same in both the single-slit and double-slit cases because both patterns obey

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

Therefore, the quantity that is the same in both experiments is the **slit width** a , which determines the diffraction envelope.

2. How does the distance from the central maximum to the first minimum in the single-slit pattern compare to the distance from the central maximum to the first diffraction minimum in the double-slit pattern?

They are the same (within measurement uncertainty), because the first minimum in both cases comes from the identical diffraction condition

$$a \sin \theta = \lambda.$$

Changing from one slit to two slits introduces interference fringes, but the outer envelope and thus the first minimum remains determined only by a . Experimentally, the distances measured in the single-slit and double-slit scans match to within the propagated uncertainties.

3. What physical quantity determines where the amplitude of the interference peaks goes to zero?

The zeros of the interference peaks occur at the minima of the diffraction envelope, which are determined by the **slit width** a . Mathematically, the factor

$$\left(\frac{\sin \alpha}{\alpha}\right)^2, \quad \alpha = \frac{\pi a}{\lambda} \sin \theta$$

multiplicatively suppresses the interference pattern. Thus, the interference maxima go to zero exactly when the diffraction envelope equals zero.

4. In theory, how many interference maxima should be in the central envelope for a double slit with $d = 0.25$ mm and $a = 0.04$ mm?

The number of interference maxima in the central diffraction envelope is given by

$$N = \frac{2d}{a}.$$

Substituting the values,

$$N = \frac{2(0.25 \text{ mm})}{0.04 \text{ mm}} = 12.5.$$

Since the number of maxima must be an integer, the theoretical prediction is

12 interference maxima in the central envelope.

5. How many interference maxima are actually in the central envelope?

From the experimental data (Figure 3), the central diffraction envelope contains

11 interference maxima

which is one fewer than the theoretical prediction of 12. This occurs because the outermost predicted maximum lies very close to the first diffraction minimum, where the diffraction envelope suppresses the intensity almost to zero. The sensor resolution and the reduced signal near the envelope boundary make this outer maximum too faint to be detected in the measured pattern. The observed value of 11 is therefore consistent with the expected envelope behavior and the limitations of the measurement apparatus.

4 Conclusion

The experiment successfully measured diffraction and interference patterns and showed that the position of the diffraction minima depends only on the slit width. The results from both manual feature analysis and model fitting produced consistent values for the slit width and slit separation. The interference maxima were observed to fall within the diffraction envelope exactly as predicted, and the number of maxima in the central region agreed with theory. The verification of the uncertainty relation using three different slit widths also showed strong consistency with the expected value. Overall the measurements support the theoretical descriptions of single slit diffraction, double slit interference, and the connection to photon momentum uncertainty.

5 References

- [1] C. Lee and T. Vahabi, *Interference and Diffraction of Light*. University of Toronto, Toronto, Canada, current revision 30710f6, Nov. 20, 2025.

6 Appendix

6.1 Appendix A: Python Code for Double Slit Analysis

The following Python script was used to analyze the double slit intensity data. The code loads the measured file, smooths the data, recenters the pattern, and fits the full diffraction and interference model.

```

1 import numpy as np
2 import matplotlib.pyplot as plt
3 from scipy.optimize import curve_fit
4 from scipy.ndimage import gaussian_filter1d
5
6 lam = 650e-9
7 L = 1.00
8
9 file_path = "/Users/amirk/Desktop/phy293_code/diffraction_data.txt" #
10     This is the pathline used ffrom my computer change this line to
11     where the data is stored in order to work this out.
12 data = np.loadtxt(file_path, skiprows=2)
13
14 x = data[:, 0]
15 I = data[:, 1]
16
17 I = np.clip(I, 0, None)
18 I_smooth = gaussian_filter1d(I, sigma=2)
19 I_norm = I_smooth / np.max(I_smooth)
20 x_centered = x - x[np.argmax(I_norm)]
21
22 def double_slit(x, I0, a, d):
23     theta = np.arctan(x / L)
24     alpha = (np.pi * a / lam) * np.sin(theta)
25     beta = (np.pi * d / lam) * np.sin(theta)
26     alpha = np.where(alpha == 0, 1e-12, alpha)
27     return I0 * (np.sin(alpha)/alpha)**2 * (np.cos(beta))**2
28
29 a_expected = 0.08e-3
30 d_expected = 0.25e-3
31
32 initial_guess = [1.0, a_expected, d_expected]
33 bounds_lower = [0, 0.01e-3, 0.10e-3]
34 bounds_upper = [5, 0.20e-3, 0.40e-3]
35
36 params, _ = curve_fit(
37     double_slit,
38     x_centered,
39     I_norm,
40     p0=initial_guess,
41     bounds=(bounds_lower, bounds_upper),
42     maxfev=20000
43 )
44
45 I0_fit, a_fit, d_fit = params
46
47 print("=====FIT_RESULTS=====")
48 print(f"I0:{I0_fit}")
49 print(f"a slit width: {a_fit:.6e}m({a_fit*1e3:.4f}mm)")
50 print(f"d(separation): {d_fit:.6e}m({d_fit*1e3:.4f}mm)")

```

```

49
50 plt.figure(figsize=(11,5))
51 plt.plot(x_centered, I_norm, ".", markersize=3, label="Data")
52 plt.plot(x_centered, double_slit(x_centered, I0_fit, a_fit, d_fit), "--",
53         , label="Fit")
54 plt.xlabel("Position(m)")
55 plt.ylabel("Normalized_Intensity")
56 plt.legend()
57 plt.grid(True)
58 plt.show()

```

Listing 1: Double Slit Python Analysis

6.2 Appendix B: Python Code for Feature-Based Slit Measurement

This script implements the manual feature-based analysis described in the laboratory manual. It removes invalid scan regions, smooths the measured intensity data, identifies the interference maxima used to determine the slit separation d , and detects the diffraction minima used to determine the slit width a . No curve fitting is used.

```

1  import numpy as np
2  import matplotlib.pyplot as plt
3  from scipy.signal import find_peaks
4  from scipy.ndimage import gaussian_filter1d
5
6  lam = 650e-9
7  L   = 1.00
8
9  file_path = "/Users/amirk/Desktop/phy293_code/diffraction_data.txt"
10 data = np.loadtxt(file_path, skiprows=2)
11
12 x = data[:,0]
13 I = data[:,1]
14
15 mask = (x != 0.0)
16 x = x[mask]
17 I = I[mask]
18
19 I = np.clip(I, 0, None)
20 I_s = gaussian_filter1d(I, sigma=2)
21 I_s /= np.max(I_s)
22
23 x0 = x[np.argmax(I_s)]
24 x_c = x - x0
25
26 peaks, props = find_peaks(I_s, height=0.4, distance=60)
27 xp = x_c[peaks]
28 xp = xp[np.abs(xp) > 0.002]
29 xp = xp[np.abs(xp) < 0.015]
30
31 d_vals = []
32 for xpk in xp:
33     theta = np.arctan(xpk / L)
34     d_vals.append(lam / np.sin(theta))
35
36 d_est = np.mean(np.abs(d_vals))
37

```

```

38 minima, _ = find_peaks(-I_s, distance=120)
39 xm = x_c[minima]
40 deep = np.argsort(I_s[minima])[:2]
41 xm = xm[deep]
42
43 a_vals = []
44 for xm1 in xm:
45     theta = np.arctan(xm1 / L)
46     a_vals.append(lam / np.sin(theta))
47
48 a_est = np.mean(np.abs(a_vals))
49
50 print(f"Estimated_slit_separation_d:{d_est*1e3:.4f}mm")
51 print(f"Estimated_slit_width_a:{a_est*1e3:.4f}mm")
52
53 plt.figure(figsize=(10,5))
54 plt.plot(x_c, I_s, label="Smoothed_Data")
55 plt.plot(xp, np.interp(xp, x_c, I_s), 'ro', label="Interference_Maxima(d)")
56 plt.plot(xm, np.interp(xm, x_c, I_s), 'ko', label="Diffraction_Minima(a)")
57 plt.xlabel("Position(m)")
58 plt.ylabel("Normalized_Intensity")
59 plt.legend()
60 plt.grid(True)
61 plt.title("Detected_Maxima_and_Minima")
62 plt.show()

```

Listing 2: Python script for computing slit width and slit separation without fitting

6.3 Error Propagation in the Slit Width a

From the first–minimum condition for single-slit diffraction,

$$a = \frac{\lambda L}{l},$$

where λ , L , and l are independent measured quantities.

Partial derivatives:

$$\frac{\partial a}{\partial \lambda} = \frac{a}{\lambda}, \quad \frac{\partial a}{\partial L} = \frac{a}{L}, \quad \frac{\partial a}{\partial l} = -\frac{a}{l}.$$

Uncertainty propagation:

$$u_a^2 = \left(\frac{a}{\lambda}u_\lambda\right)^2 + \left(\frac{a}{L}u_L\right)^2 + \left(\frac{a}{l}u_l\right)^2,$$

6.4 Error Propagation in the Slit Spacing d

From the double-slit interference condition,

$$d \sin \theta = m\lambda,$$

and using the small-angle geometry,

$$\theta \approx \tan^{-1}\left(\frac{x}{L}\right) \approx \frac{x}{L},$$

the slit spacing for order m is

$$d = \frac{m \lambda L}{x}.$$

Treating d as a function of the independent variables λ , L , and x ,

$$d(\lambda, L, x) = \frac{m \lambda L}{x}.$$

Partial derivatives:

$$\frac{\partial d}{\partial \lambda} = \frac{mL}{x} = \frac{d}{\lambda}, \quad \frac{\partial d}{\partial L} = \frac{m\lambda}{x} = \frac{d}{L}, \quad \frac{\partial d}{\partial x} = -\frac{m\lambda L}{x^2} = -\frac{d}{x}.$$

Uncertainty propagation:

$$u_d^2 = \left(\frac{\partial d}{\partial \lambda} u_\lambda \right)^2 + \left(\frac{\partial d}{\partial L} u_L \right)^2 + \left(\frac{\partial d}{\partial x} u_x \right)^2,$$

so

$$u_d^2 = \left(\frac{d}{\lambda} u_\lambda \right)^2 + \left(\frac{d}{L} u_L \right)^2 + \left(\frac{d}{x} u_x \right)^2,$$

6.5 Error Propagation for the Uncertainty Principle

Define

$$Q(a, \lambda, l, b) = \frac{a}{\lambda} \sin\left(\tan^{-1} \frac{l}{b}\right),$$

with independent uncertainties in a , λ , l , and b .

Let

$$\theta = \tan^{-1} \frac{l}{b}.$$

Partial derivatives:

$$\frac{\partial Q}{\partial a} = \frac{1}{\lambda} \sin \theta = \frac{Q}{a}, \quad \frac{\partial Q}{\partial \lambda} = -\frac{a}{\lambda^2} \sin \theta = -\frac{Q}{\lambda},$$

$$\frac{\partial Q}{\partial l} = \frac{a}{\lambda} \cos \theta \frac{b}{b^2 + l^2} = Q \cot \theta \frac{b}{b^2 + l^2},$$

$$\frac{\partial Q}{\partial b} = -\frac{a}{\lambda} \cos \theta \frac{l}{b^2 + l^2} = -Q \cot \theta \frac{l}{b^2 + l^2}.$$

Uncertainty propagation:

$$u_Q^2 = \left(\frac{\partial Q}{\partial a} u_a \right)^2 + \left(\frac{\partial Q}{\partial \lambda} u_\lambda \right)^2 + \left(\frac{\partial Q}{\partial l} u_l \right)^2 + \left(\frac{\partial Q}{\partial b} u_b \right)^2,$$